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Technical Report

WATER VAPOR TRANSMISSION OF CONCRETE AND OF AGGREGATES

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WATER VAPOR TRANSMISSION OF CONCRETE AND OF AGGREGATES

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by

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ABSTRACT

An investigation was made of the effects of water-cement ratio, type of reinforcing steel, aggregate size, relative humidity, concrete slice position, and two admixtures, sodium chloride and oleic acid, on the water vapor transmission of concrete. A collateral investigation was made of the water vapor transmission of aggregates, and a study was made of the growth of sodium chloride whisker crystals on concrete.

Water vapor transmission rates were found to decrease with an increase in strength of concrete (decreased water-cement ratio), an increase in aggregate size, and the presence of sodium chloride. Rates appeared to decrease with an increase in relative humidity, but the data were inconclusive. The rates were found to be independent of the type of reinforcing steel and the absence or presence of oleic acid.

The water vapor transmission rates of aggregates were found to be lower than the water vapor transmission rates of concrete, but were of the same order of magnitude.

Whisker crystals were observed to be growing only on concrete specimens which contained sodium chloride. The amounts of growth were observed to be larger on lower strengths of concrete.

Quarter-replicate and half-replicate experiments were used successfully to determine water vapor transmission rates, thereby reducing the required number of specimens.

Copies available at OTS $1.75.
The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

CONTENTS

INTRODUCTION

The investigation of the water vapor transmission of concrete has been in progress at the Naval Civil Engineering Laboratory for a period of 3 years. The purpose of the investigation is to determine the effects of strength of concrete (water-cement ratio), maximum aggregate size, type of reinforcing steel, ambient relative humidity, and two admixtures, sodium chloride and oleic acid, on the water vapor transmission of concrete. Reference 1 includes the results of a much more detailed investigation of the effect of sodium chloride. The investigation is being conducted in three phases: Phases I, II, and III. Phases I and II were begun approximately 3 years ago. Phase I is a full-replicate investigation, whereas Phase II is a statistically designed quarter-replicate investigation. Phase II is verified by Phase I. Phase III was begun approximately 2 years ago. Phase III is a statistically designed half-replicate investigation and includes variables not included in Phases I and II.

References 2 and 3 included the results of a 100-day period (from 80 to 180 days age) of Phases I and II. The present report reviews the results of the 100-day period and includes the results of a 480-day period (from 400 to 880 days age). Thus the present report includes a comparison of the short- and long-term effects in Phases I and II. It further includes the results of a 300-day period (from 350 to 650 days age) of Phase III. It also contains a discussion of sodium chloride whisker crystal growth on concrete specimens of the water vapor transmission investigation of Phase III. Similar growth on concrete specimens of Phases I and II was described in detail in Reference 2.

In addition to including the results of the water vapor transmission investigations, the present report includes the results of a 546-day compressive-strength investigation. This compressive-strength investigation was carried out in conjunction with Phase III and utilized the concrete mixes of Phase III. Concretes for all three phases are shown in Appendix A.

The report also contains the results of a collateral investigation of the water vapor transmission of aggregates. The results of this investigation are compared with the results of the investigations of the water vapor transmission of concrete containing these aggregates.

An investigation of the electrical resistivity of concrete was begun approximately 1 year ago and was carried on for 182 days of record. Within this investigation an attempt was made to correlate electrical resistivity with corrosion of reinforcing steel. The results were so inconclusive as to be meaningless and are not included herein. Further research needs to be done in this area.

Part 1. WATER VAPOR TRANSMISSION OF CONCRETE

PHASES I AND II

Description of Variables and Statistical Design

The variables and the mixing and casting procedures of Phase I and of Phase II are described in detail in Reference 2; therefore, only a list of the variables will be included in this report.

Phase I involved four variables: strength of concrete, absence or presence of sodium chloride (NaCl), ambient relative humidity (RH), and location of slice cut from each cylinder in the as-cast position. (See Table I for details.) The total number of possible combinations of variables is 36. A full-replicate experiment was used.

Phase II involved six variables: the four variables of Phase I plus maximum aggregate sizes and absence or presence of oleic acid. (See Table II for details.) The total number of possible combinations of variables is 64. A statistically designed quarter-replicate experiment (i.e., one having 16 combinations) was used. Phase II had more variables than Phase I, but took less than half the number of wet cups.

The results of Phase II (quarter replicate) compared to Phase I (full replicate) as reported in Reference 2 verified the validity of a fractional factorially designed experiment, by statistically designing the experiment and by statistically analyzing the results for significant variables. It is because of the agreement between Phases I and II that Phase III, which is a statistically designed half-replicate experiment, can be used reliably.

Recapitulation: 100-Day Period

A recapitulation of the findings as reported in Reference 2, an interim report on this task, discloses the following.

Water vapor transmission (WVT) decreased with a decrease in water-cement ratio (increase in strength), an increase in aggregate size, and the presence of NaCl. WVT was not significantly affected by concrete slice position, presence of oleic acid, and RH when compared with experimental variability. The form of Fick's Law, which is commonly used to determine water vapor permeability of concrete, was not verified. An equation for WVT = Wl/At was thought to be more suitable for the observed phenomenon than was Fick's Law (however, this equation has since been revised — see below). There was an optimum concentration of NaCl for maximum compressive strength of concrete with a given high water-cement ratio; however, concrete with 1.5 percent NaCl by weight of fresh concrete had less strength than concrete without NaCl, other factors being equal. At 14 days age, concrete containing small aggregate (maximum size 3/8 inch) was stronger than concrete containing large aggregate (maximum size 3/4 inch) for identical water-cement ratios.

Revision of WVT Formula

For the 100-day period of Phases I and II, WVT was calculated using the following formula from page 17 of Reference 2:

$$WVT = \frac{Wl}{At}, \text{ inch-grains per square inch per day}$$

where W = weight of water vapor transmitted, grains (1 gram = 15.43 grains)

l = length of flow path (or thickness of specimen), inches

A = area of cross section of flow path, square inches

t = time during which water vapor transmission occurred, days

This formula was adopted for these studies because other methods of calculating water vapor permeability (WVP), as presented in ASTM Designation E96-53T, showed incompatibility among similar specimens. The apparent fact that WVP is not a correct method of expressing the movement of water through concrete (a hygroscopic material) is further supported by References 4 and 5.

After further investigation and study, as reported in Reference 1, it was determined from experimental results that the length of flow path had little or no effect upon WVT rates. Therefore, the following revised formula for calculating WVT was adopted and used in this report:

$$WVT = \frac{W}{At} = \frac{W}{t} C_A, \text{ grains per square inch per day}$$

where W = weight of water vapor transmitted, grams

A = Area of cross section of flow path, square inches

t = time during which water vapor transmission occurred, days

C_A = coefficient inversely proportional to the cross-sectional area of the specimen

= $1/A$

= 15.43 grains per gram $\div$ A, grains per gram per square inch

= $15.43 \div 26.06 = 0.592$ for 6-inch-diameter specimen

= $15.43 \div 11.12 = 1.388$ for 4-inch-diameter specimen

This new equation indicates that WVT is not dependent upon the length of flow path (thickness of specimen) for the specific thicknesses (1 1/2, 2, and 3 inches) studied in this experiment.

Discussion of Results

Phase I. Phase I has been in progress for approximately 910 days (2-1/2 years). The first reports (References 2 and 3) covered data for a 100-day period (from 80 to 180 days age) and reported WVT rates for that period. Table I presents that 100-day period in comparison to a 480-day period (from 400 to 880 days age) for the same wet cups (noted as old and new, respectively). Table I contains the old values of WVT converted to the new units (grains per square inch per day) for the 100-day period and the new values of WVT for the 480-day period. In all cases, the new WVT values are lower. It also appears that specimens without NaCl show a greater decrease (a shift downward in range values) in WVT values than do those with NaCl, as shown in Figures 1a and 1b.

Figures 1a and 1b show graphically the effect of age and the effect of the variables upon WVT during the 100-day and 480-day periods. Figure 1a is a plot of the old converted WVT values versus W/C ratio for concrete with large aggregate, with and without NaCl, at 20 and 50 percent RH, for the 100-day period as reported in References 2 and 3. Figure 1b is the same except that it is for the 480-day period.

Figures 1a and 1b show that age has a direct effect upon WVT for the specimens under consideration. The same specimens have lower WVT values for the 480-day period than they do for the 100-day period (i.e., WVT decreases as age increases). Although the WVT values are shifted down relative to one another, WVT rates for the 100-day and 480-day periods decrease with an increase in strength of concrete and for concrete with 1.5 percent NaCl. Figure 1b indicates that increasing RH slightly decreases WVT. The slight affect of RH was not definitely established during the 100-day period (Figure 1a) but was definitely established during the 480-day period (Figure 1b). However, no other differences exist between the conclusions for the old period and the conclusions for the new period as far as the effects of the variables are concerned.

Phase II. Phase II has been in progress for approximately 880 days (nearly 2-1/2 years). The first reports (References 2 and 3) covered data for a 100-day period (from 80 to 180 days age) and reported WVT rates for that period. Table II presents that 100-day period in comparison to a 480-day period (from 400 to 880 days age) for the same wet cups (noted as old and new, respectively). Table II has the old values of WVT converted to the new units (grains per square inch per day) for the 100-day period and the new values of WVT for the 480-day period.

Figures 2a and 2b show graphically the effect of age and the effect of the variables upon WVT during the 100-day and 480-day periods. Figure 2a is a plot of the old converted WVT values versus W/C ratio for concrete with large and small aggregate, with and without NaCl, at 20 and 50 percent RH, for the 100-day period reported in References 2 and 3. Figure 2b is the same except that it is for the 480-day period. In Phase II the specimens were changed from one RH condition to the other RH condition (i.e., the specimens originally in the 20-percent RH room were moved to the 50-percent RH room and visa versa). This change was made at an average age of 180 days (i.e., at the end of the 100-day period) for all specimens in order to investigate further the effect of RH on WVT.

Figures 2a and 2b show that all WVT values are lower for the 480-day period than for the 100-day period. Figure 2b indicates that increasing RH from 20 to 50 percent decreases WVT (i.e., WVT rates for 20 percent RH are higher than WVT rates for 50 percent RH). The effect of RH was not clearly established during the 100-day period (Figure 2a) but was definitely established during the 480-day period (Figure 2b). This establishment of the effect of RH during only the 480-day period was observed also in Phase I; however, since Phase I included only concrete containing large aggregate, Phases I and II are not entirely comparable.

Table I. WVT (Old and New) and Design Variables - Phase I

Batch No.	Cup No. a/	Strength b/	NaCl c/	RH d/	Old WVT e/	Old Conv. WVT f/	New W/t g/	New WVT h/
1L	N572T	L	A	H	—	—	0.162	—
1L	N572M	L	A	H	0.537	0.356	0.181	0.237
1L	N572B	L	A	H	—	—	0.170	—
1LS	N610T	L	P	H	—	—	0.114	—
1LS	N610M	L	P	H	0.298	0.197	0.120	0.167
1LS	N610B	L	P	H	—	—	0.127	—
1M	N671T	M	A	H	—	—	0.102	—
1M	N671M	M	A	H	0.356	0.237	0.125	0.161
1M	N671B	M	A	H	—	—	0.120	—
1MS	N683T	M	P	H	—	—	0.058	—
1MS	N683M	M	P	H	0.190	0.125	0.055	0.076
1MS	N683B	M	P	H	—	—	0.052	—
1H	N734T	H	A	H	—	—	0.051	—
1H	N734M	H	A	H	0.226	0.151	0.071	0.086
1H	N734B	H	A	H	—	—	0.065	—
1HS	N759T	H	P	H	—	—	0.034	—
1HS	N759M	H	P	H	0.121	0.081	—	0.050
1HS	N759B	H	P	H	—	—	0.037	—
1L	N579T	L	A	L	—	—	0.200	—
1L	N579M	L	A	L	0.617	0.401	0.180	0.276
1L	N579B	L	A	L	—	—	0.216	—
1LS	N599T	L	P	L	—	—	0.131	—
1LS	N599M	L	P	L	0.280	0.189	—	0.186
1LS	N599B	L	P	L	—	—	0.137	—
1M	N660T	M	A	L	—	—	0.135	—
1M	N660M	M	A	L	0.362	0.244	0.139	0.193
1M	N660B	M	A	L	—	—	0.143	—
1MS	N700T	M	P	L	—	—	0.063	—
1MS	N700M	M	P	L	0.172	0.115	0.070	0.091
1MS	N700B	M	P	L	—	—	0.064	—
1H	N719T	H	A	L	—	—	0.090	—
1H	N719M	H	A	L	0.259	0.173	0.099	0.139
1H	N719B	H	A	L	—	—	0.110	—
1HS	N755T	H	P	L	—	—	0.051	—
1HS	N755M	H	P	L	0.133	0.088	0.053	0.077
1HS	N755B	H	P	L	—	—	0.063	—

a/ T, M, B: Top, middle, or bottom slice from cylinder as-cast.
b/ L, M, H: Low, medium, or high strength; e.g., W/C = 0.702, 0.571, and 0.444 respectively.
c/ A, P: Absence or presence of NaCl (1.5 percent by weight of fresh concrete). For the values of W/C shown in Note b, the salt - cement ratios are 0.133, 0.108, and 0.084 respectively.
d/ L, H: 20 percent or 50 percent RH at 73.4 F.
e/ Average WVT from Reference 2 as calculated by Wl/At, inch-grains per square inch per day. For 100-day period (80-180 days age).
f/ Converted to $(W/t)C_A$, grains per square inch per day. For 100-day period.
g/ Slope of graph of weight loss versus time, grams per day. For 480-day period (400-880 days age).
h/ Grains per square inch per day. For 480-day period.

Note: All concrete had aggregate with maximum size of 3/4 inch.

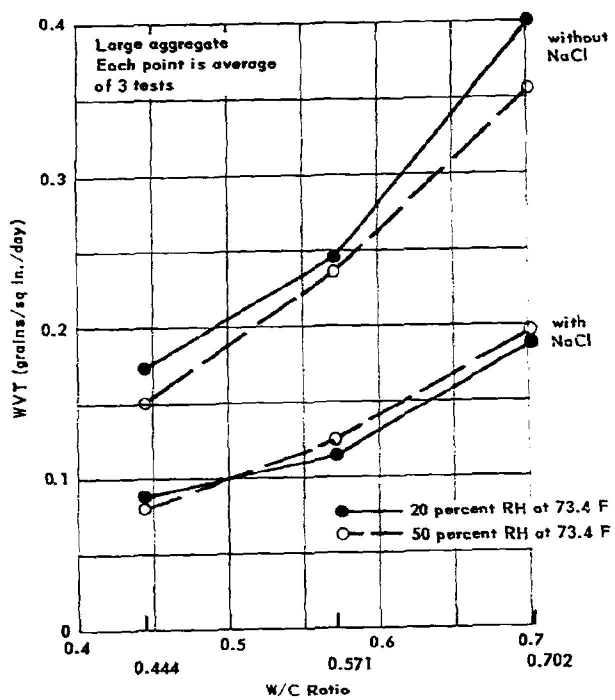

Figure 1a. WVT versus W/C ratio – Phase I, 100-day period (from 80 to 180 days age).

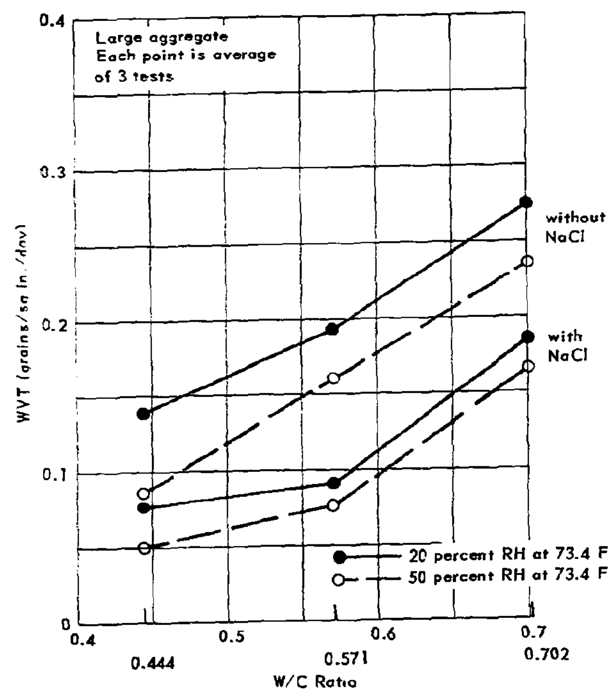

Figure 1b. WVT versus W/C ratio – Phase I, 480-day period (from 400 to 880 days age).

Table II. WVT (Old and New) and Design Variables - Phase II

Batch No.	Cup No. a/	Strength b/	Aggregate c/	NaCl d/	Oleic Acid e/	Original RH f/	Present RH g/	Old WVT h/	Old Conv. WVT i/	New W/t j/	New WVT k/
S-1	N872B	L	S	A	A	L	H	0.714	0.477	0.166	0.231
S-2	P124T	H	L	A	P	L	H	0.292	0.194	0.073	0.101
S-3	N990T	H	S	P	A	H	L	0.274	0.183	0.094	0.131
S-4	P180B	L	L	P	P	H	L	0.329	0.215	0.107	0.149
S-5	P-66B	H	L	P	A	L	H	0.185	0.125	0.043	0.060
S-6	P248B	H	S	A	P	H	L	0.381	0.254	0.134	0.185
S-7	N852T	L	L	A	A	H	L	0.558	0.376	0.231	0.321
S-8	P385T	L	S	P	P	L	H	0.443	0.287	0.147	0.203
S-9	N947T	H	S	A	A	L	H	0.389	0.258	0.088	0.121
S-10	P214B	L	L	A	P	L	H	0.581	0.393	0.180	0.249
S-11	N919B	L	S	P	A	H	L	0.376	0.248	0.150	0.208
S-12	P147T	H	L	P	P	H	L	0.160	0.107	0.057	0.078
S-13	P-38B	H	L	A	A	H	L	0.281	0.186	0.102	0.142
S-14	P296B	H	S	P	P	L	H	0.228	0.150	0.052	0.073
S-15	P-17T	L	L	P	A	L	H	0.408	0.272	0.138	0.191
S-16	P344T	L	S	A	P	H	L	0.817	0.535	0.336	0.467

a/ T, B: Top or bottom slice. See Note a/ of Table I.
b/ L, H: Low or high strength. See Note b/ of Table I.
c/ S, L: Small (3/8-inch) or large (3/4-inch) maximum aggregate size.
d/ A, P: Absence or presence of NaCl. See Note c/ of Table I; for 3/8-inch maximum aggregate size the salt - cement ratios were 0.128 and 0.081 for W/C values of 0.702 and 0.444 respectively.
e/ A, P: Absence or presence of oleic acid.
f/ L, H: *20 percent or 50 percent RH at 73.4 F during 100-day period (80-180 days age).*
g/ L, H: 20 percent or 50 percent RH at 73.4 F during 480-day period (400-880 days age). Specimens were moved from one RH to the other at 180 days age.
h/ WVT from Reference 2 as calculated by Wl/At, inch-grains per square inch per day. For 100-day period.
i/ Converted to $(W/t)C_A$, grains per square inch per day.
j/ Slope of graph of weight loss versus time, grams per day. For 480-day period.
k/ Grains per square inch per day. For 480-day period.

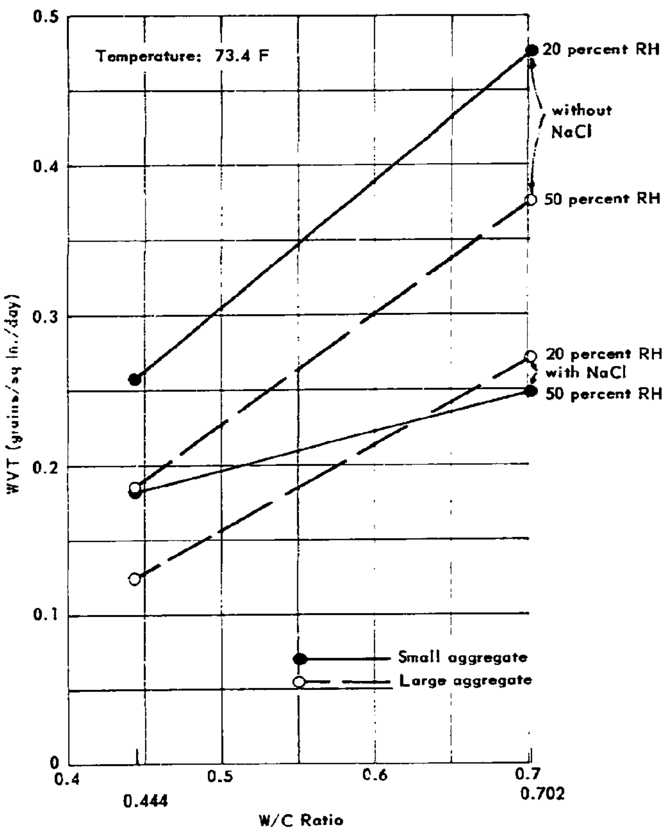

Figure 2 a. WVT versus W/C ratio - Phase II, 100-day period (from 80 to 180 days age).

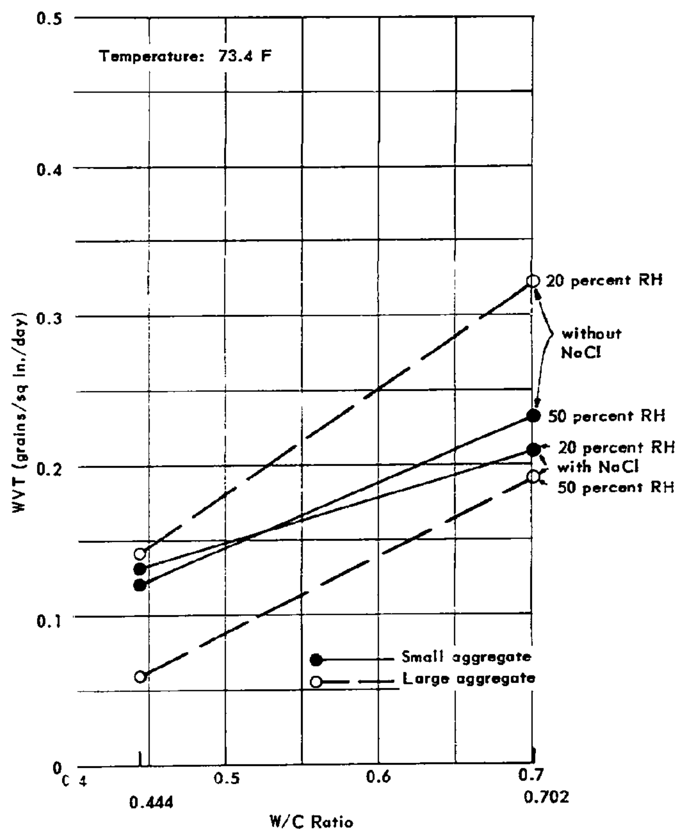

Figure 2b. WVT versus W/C ratio - Phase II, 480-day period (from 400 to 880 days age).

In general, the same conclusions may be made for Phase II as were made for Phase I (i.e., WVT decreases with an increase in strength of concrete and for concrete with 1.5 percent NaCl, and slightly decreases with an increase in RH). In addition, WVT is not affected by different maximum aggregate sizes (or else the effect is so small as to be completely hidden by the effects of the other variables).

As was done for the 100-day period of References 2 and 3, the WVT values (of Table II) for the 480-day period were subjected to an analysis of variance. This analysis, together with the analysis for the 100-day period, is presented in Table IX in Appendix B.

Table IX shows that for both the 100-day period and the 480-day period at the 5-percent level, concrete strength and NaCl are highly significant but maximum aggregate size is significant only for the 100-day period. At the 1-percent level, concrete strength and NaCl are highly significant and none of the other variables are significant. It is interesting to note that in each case the small residual error indicates that much of the variability has been accounted for in the experimental procedure and in the analysis.

In general, the analysis of variance indicates that only concrete strength and NaCl are highly significant. In fact, considering the rather large variations in quality of concrete when it is mixed under "field conditions," it seems that all other variables (maximum aggregate size, slice position, relative humidity, and oleic acid) are not significant. The results of the statistical analysis of variance agree very closely with the graphical results presented above. It should be noted that the graphs are probably only accurate enough to compare the variables with the 5-percent-level results and not with the 1-percent level.

PHASE III

Description of Variables and Statistical Design

Phase III included all of the variables of Phase II except slice position (all specimens were cut from the center of the cylinder). In addition, the effects of two types of reinforcing steel were considered. Phase III was a half-replicate experiment whereas Phase II was only a quarter-replicate experiment. There were six factors, one with three levels and five with two levels, making a total of 96 combinations in all. A statistically designed half-replicate experiment (i.e., one having 48 combinations) was used in Phase III. The design variables, identified by batch number, are presented in Table III.

Figure 3 shows the two kinds of steel grids used. The grid on the left (referred to as B steel) is constructed of 1/4-inch-diameter prestressing wire (high-strength, stress-relieved, uncoated) having an ultimate strength of 242,200 psi. The grid on the right (referred to as A steel) is constructed of No. 5 deformed reinforcing bar (5/8-inch-diameter) of mild steel with an ultimate tensile strength of 81,000 psi. The maximum diameter of either type of grid was 5-1/2 inches. The grid was cast in the center of the cylinder, from which a middle slice was taken.

Experimental Procedure

Mixing and Casting. The mixing and casting procedures for Phase III were the same as those for Phase II except for the addition of the steel grid and the use of cylinders of different sizes. All batches were mixed in a pan-type mixer, with the same sequential operations listed on page 9 of Reference 2.

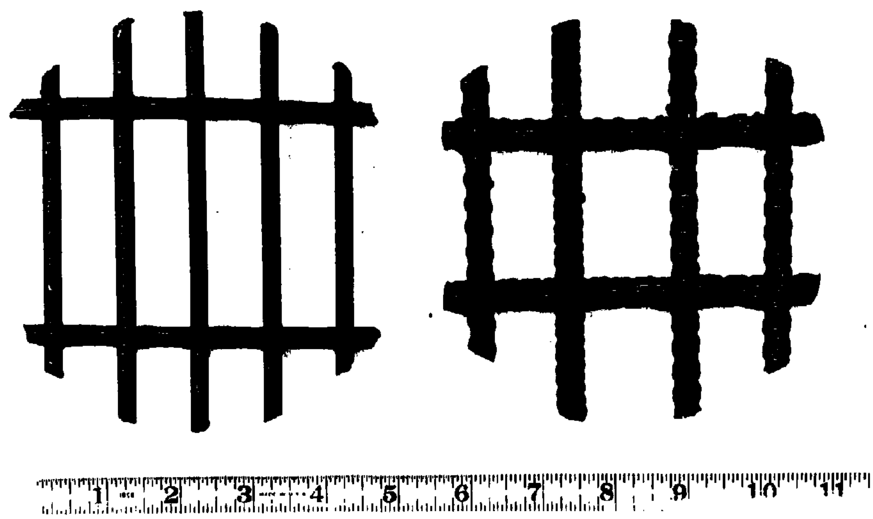

Figure 3. Two types of steel grids used in the WVT study of Phase III.

Table III. Design Variables - Phase III

Batch No. a/	Kind of Steel b/	Aggregate c/	NaCl d/	Oleic Acid e/	RH f/
SSL-1	B	S	A	A	L
SSL-2	B	S	A	P	H
SSL-3	B	S	P	P	L
SSL-4	B	S	P	A	H
SSL-5	B	L	A	A	H
SSL-6	B	L	A	P	L
SSL-7	B	L	P	P	H
SSL-8	B	L	P	A	L
SSL-9	A	S	A	A	H
SSL-10	A	S	A	P	L
SSL-11	A	S	P	P	H
SSL-12	A	S	P	A	L
SSL-13	A	L	A	A	[illegible]
SSL-14	A	L	A	P	H
SSL-15	A	L	P	P	L
SSL-16	A	L	P	A	H
SSM-1	B	S	A	A	L
SSM-2	B	S	A	P	H
SSM-3	B	S	P	P	L
SSM-4	B	S	P	A	H
SSM-5	B	L	A	A	H
SSM-6	B	L	A	P	L
SSM-7	B	L	P	P	H
SSM-8	B	L	P	A	L
SSM-9	A	S	A	A	H
SSM-10	A	S	A	P	L
SSM-11	A	S	P	P	H
SSM-12	A	S	P	A	L
SSM-13	A	L	A	A	L
SSM-14	A	L	A	P	H
SSM-15	A	L	P	P	L
SSM-16	A	L	P	A	H

Table III. Design Variables - Phase III (Cont'd)

Batch No. a/	Kind of Steel b/	Aggregate c/	NaCl d/	Oleic Acid e/	RH f/
SSH-1	B	S	A	A	L
SSH-2	B	S	A	P	H
SSH-3	B	S	P	P	L
SSH-4	B	S	P	A	H
SSH-5	B	L	A	A	H
SSH-6	B	L	A	P	L
SSH-7	B	L	P	P	H
SSH-8	B	L	P	A	L
SSH-9	A	S	A	A	H
SSH-10	A	S	A	P	L
SSH-11	A	S	P	P	H
SSH-12	A	S	P	A	L
SSH-13	A	L	A	A	L
SSH-14	A	L	A	P	H
SSH-15	A	L	P	P	L
SSH-16	A	L	P	A	H

a/ SSL, SSM, SSH: Low, medium, or high strength (see Note b/ of Table I); SS = statistical study.

b/ A, B: No. 5 deformed bar grid or 1/4-inch high-strength prestressing wire grid.

c/ S, L: Small (3/8-inch) or large (3/4-inch) maximum aggregate size.

d/ A, P: Absence or presence of NaCl (1.5 percent by weight of fresh concrete). See Notes b/ and c/ of Table I and Notes b/ and d/ of Table II.

e/ A, P: Absence or presence of oleic acid (0.25 percent by weight of cement).

f/ L, H: 20 percent or 50 percent RH at 73.4 F.

Each batch consisted of 2.25 cubic feet of concrete and was used to make one 6-inch-diameter by 12-inch cylinder for a WVT specimen and fifteen 4-inch-diameter by 8-inch cylinders for compressive-strength specimens. The steel grid was cast in the center of the 6-inch-diameter by 12-inch cylinder. In order to provide a means of assuring that the grid was in the center of the cylinder, four very small holes were drilled in the wall of the mold, and waterproof braided nylon fishing line was tied through the holes and across the mold to form a support for the grid. The mold was filled with concrete up to the nylon line (half full) and vibrated; the grid was placed on the nylon line and worked into the concrete slightly; then the mold was completely filled with concrete and vibrated with a spud vibrator in the standard manner. Figure 4 shows a steel grid being placed in a cylinder mold.

WVT. After 14 days of curing in the 73.4 F fog room, one disk 2 inches thick and containing the steel grid was sawed from the middle of the cylinder. Before being sawed, the cylinder was embedded in plaster of Paris to avoid chipping the edges of the disk at the break-through of the saw. Figure 5 shows a disk embedded in plaster of Paris. The disk was then prepared for encasement in an acrylic cup by washing, surface drying, and stamping with an identification number. The fabrication and assembly details for the acrylic cup with concrete disk (wet cup) are given in Reference 2. After assembly, the wet cup was half-filled with distilled water and placed in the appropriate RH room. Five to six hours elapsed from the time the disk was sawed to the time the cup was placed in the RH room.

Figure 6 shows an assembled wet cup. The flocculent material which appears in the water at the bottom of the cup was subjected to an X-ray and emission analysis. The results of the analysis show that the flocculent materials was mainly $CaCO_3$ (aragonite form). It contained appreciable amounts of magnesium and silicon — 3 percent each. Small amounts of aluminum and iron were detected. Since the wet cup initially contained only distilled water, the flocculent material must have come from the concrete specimen.

After the wet cup was placed in the appropriate RH room, 12 or so hours were allowed for it to reach the 73.4 F temperature of the room and then an initial weighing was made. Thereafter, weighings were made every 7 days for 2 weeks and then every 28 days for the remainder of the test period. All weighings were made in the RH room in which the wet cup was stored. The weighings were made to the nearest gram (and estimated to the nearest half gram), and the weight loss thus determined was plotted versus time. Figure 7 is a plot of weight loss versus time for a typical wet cup.

Figure 4. Placing steel grid in cylindrical mold.

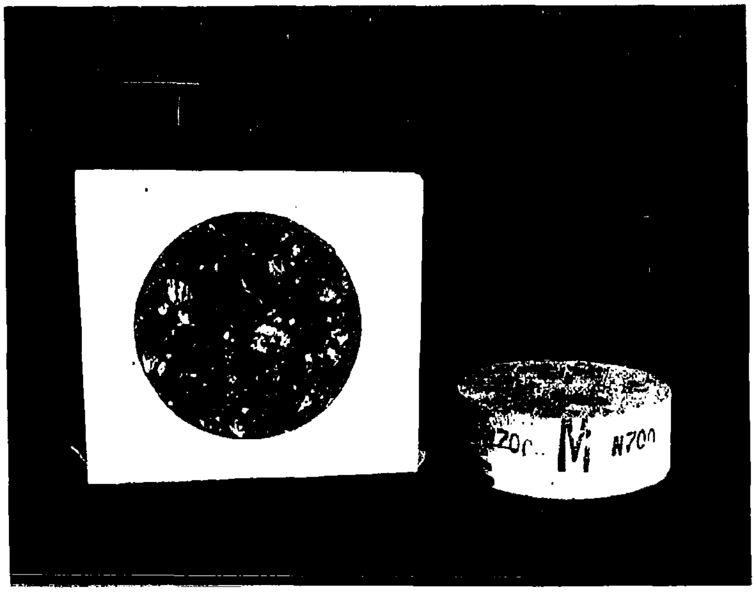

Figure 5. Plaster of Paris casting around concrete cylinder to prevent chipping of concrete at breakthrough of stone saw.

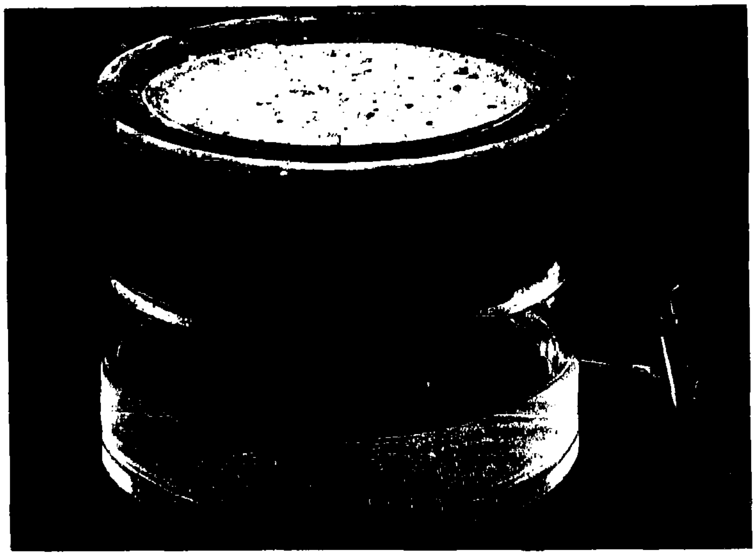

Figure 6. Assembled acrylic wet cup, including concrete specimen and water.

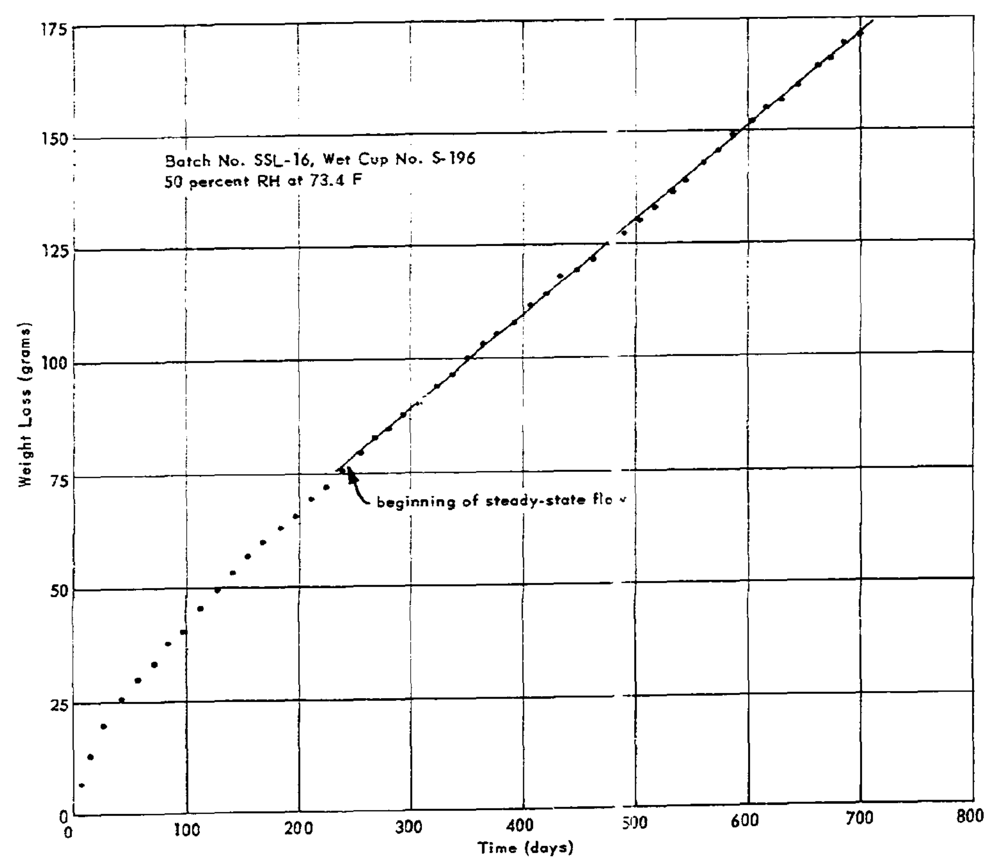

Figure 7. Weight loss versus time for a typical wet cup – Phase III.

Compressive Strength. All of the 4-inch-diameter by 8-inch cylinders of each batch were stored in the fog room until the day they were used in a compressive-strength test. Tests were performed at five different ages: 2 weeks, 4 weeks, 26 weeks, 52 weeks, and 78 weeks. Three cylinders per batch were used for each compressive-strength test.

Discussion of Results

WVT. WVT was calculated by means of the formula WVT = $(W/t)C_A$ (discussed above in the section, "Revision of WVT Formula"). Since Phase III included only 6-inch-diameter specimens, C_A = 0.592. W/t is the slope of the graph of weight loss versus time. The WVT values for a 300-day period (from 350 to 650 days age) of Phase III are presented in Table IV.

In analyzing the results of the WVT experiment, it was necessary to determine two items: first, the significance of the variables (i.e., whether or not the variables significantly affect WVT), and second, in what manner the significant variables affect WVT. Two methods were available for determining the significance of the variables:

1. Graphical analysis

2. Statistical analysis (i.e., analysis of variance)

Phase III was a statistically designed half-replicate experiment; consequently, for a given W/C ratio, no two specimens had more than three out of five variables which were the same. Statistical analysis was used to determine the significance of the variables. The WVT values of Table IV were subjected to an analysis of variance, which is presented in Table XI in Appendix C. Table XI shows that at both 5- and 1-percent significance levels, strength of concrete and NaCl are highly significant, maximum aggregate size and RH are significant, and type of steel and oleic acid are not significant.

Once it was determined statistically which variables were highly significant, a graphical analysis could be performed to determine the manner in which they affect WVT. The WVT values of Table IV are presented graphically in Figures 8, 9, 10, and 11. Since the analysis of variance shows that the type of steel and oleic acid are not significant, these variables are disregarded in the graphs.

Figures 8a and 8b show that increasing the strength of concrete (i.e., decreasing the W/C ratio) greatly decreases WVT. These graphs suggest that if a sufficiently high-strength concrete could be produced, the WVT rate could be reduced to zero (or, more realistically, to some very low rate). Because of the irregularity of the graphs of Figures 8a and 8b (some are straight, some bend up, and some bend down) the graphs were drawn as broken straight lines rather than as smooth curves. The irregularity is thought to be due to random variation in the data as well as to the effect of unknown variables in the investigation.

Figures 9a and 9b show that the presence of NaCl (1.5 percent by weight of fresh concrete) greatly decreases WVT. Figure 9a indicates an interaction between strength and NaCl. This interaction is shown by the fact that the addition of NaCl produces a greater numerical decrease in WVT for low-strength concrete than for high-strength concrete. The analysis of variance shows that this interaction is significant (see Appendix C).

Figures 10a and 10b show that, for small and large aggregate with and without NaCl, increasing the RH from 20 to 50 percent slightly decreases WVT. The analysis of variance shows that RH is significant (see Appendix C). A close agreement is seen to exist between the statistical and graphical results.

The significance of RH is, however, questionable. The exposed horizontal surfaces of all of the specimens in the 50-percent RH room were lightly coated with a hard, white crust. This crust is definitely traceable to precipitate from the extremely hard water used to maintain the humidity in the room. The specimens in the 20-percent RH room were not coated. It is thought that possibly this crust has acted to decrease the WVT. Unfortunately, a new variable may have been introduced. It is expected that increasing RH would decrease WVT, or at least would not increase WVT (e.g., at 100 percent RH the WVT rate would be zero). If the crust decreases WVT, and since the crust is present only in the 50-percent RH room, it seems quite possible that the crust has amplified the affect of RH. The effect of RH as measured in Phase III is small; therefore, it is even possible that this effect is due not to RH but to the crust on the specimens in the 50-percent RH room. It is impossible to discern from the results of the present study which of the two variables, RH or crust on the specimens, produced the "effect of RH." The problem of the crust on the specimens is also discussed in Reference 1.

Figures 11a and 11b show that, for small and large aggregate with and without NaCl, increasing the maximum aggregate size from 3/8 inch to 3/4 inch slightly decreases WVT. The analysis of variance shows that maximum aggregate size is significant (see Appendix C). As was found for RH, a close agreement exists between the statistical and graphical results.

Table IV. WVT - Phase III

Batch No.[a]	Cup No.	W/t [b]	WVT [c]
SSL-1	S212	0.678	0.401
SSL-2	S256	0.560	0.332
SSL-3	S272	0.386	0.229
SSL-4	S296	0.319	0.189
SSL-5	S240	0.558	0.330
SSL-6	S312	0.544	0.322
SSL-7	S328	0.253	0.150
SSL-8	S344	0.299	0.177
SSL-9	S360	0.615	0.364
SSL-10	S129	0.663	0.392
SSL-11	S416	0.326	0.193
SSL-12	S376	0.383	0.227
SSL-13	S148	0.551	0.326
SSL-14	S164	0.512	0.303
SSL-15	S180	0.282	0.167
SSL-16	S196	0.206	0.122
SSM-1	T274	0.590	0.350
SSM-2	T290	0.487	0.288
SSM-3	T306	0.207	0.123
SSM-4	T322	0.172	0.102
SSM-5	T362	0.318	0.188
SSM-6	T411	0.447	0.265
SSM-7	T427	0.200	0.118
SSM-8	T443	0.135	0.080
SSM-9	T564	0.438	0.259
SSM-10	T614	0.570	0.337
SSM-11	T630	0.209	0.124
SSM-12	T663	0.317	0.188
SSM-13	T679	0.395	0.234
SSM-14	T743	0.305	0.181
SSM-15	T795	0.166	0.098
SSM-16	T847	0.113	0.067

Table IV. WVT - Phase III (Cont'd)

Batch No.[a]	Cup No.	W/t [b]	WVT [c]
SSH-1	T941	0.352	0.208
SSH-2	T993	0.274	0.162
SSH-3	U34	0.126	0.075
SSH-4	U86	0.101	0.060
SSH-5	U126	0.226	0.134
SSH-6	U142	0.285	0.169
SSH-7	U182	0.082	0.049
SSH-8	U198	0.110	0.065
SSH-9	U214	0.283	0.168
SSH-10	U230	0.345	0.204
SSH-11	U246	0.106	0.063
SSH-12	U262	0.129	0.076
SSH-13	U290	0.273	0.162
SSH-14	U234	0.203	0.120
SSH-15	U340	0.118	0.070
SSH-16	U356	0.076	0.045

a/ SSL, SSM, SSH: See Note a/ of Table III.

b/ Slope of the graph of weight loss versus time, grams per day.

c/ WVT = $(W/t)C_A$ (for 6-inch-dia. disk, $C_A = 0.592$), grains per square inch per day. For a 300-day period (350-650 days age).

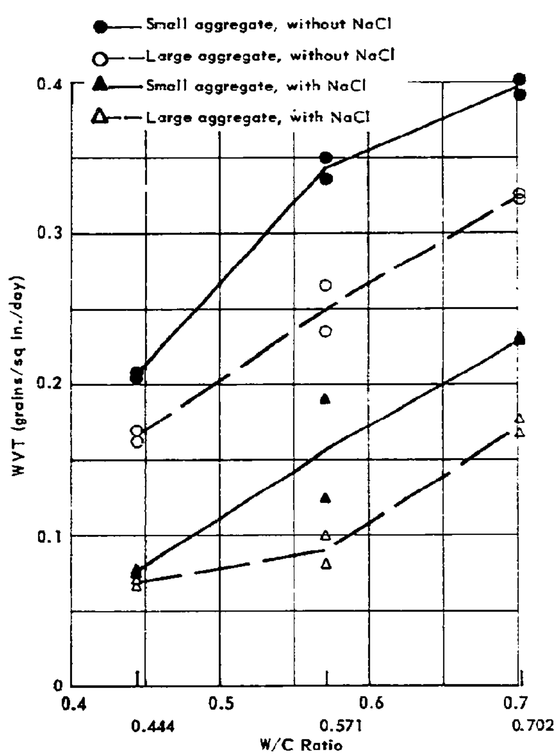

Figure 8a. WVT versus W/C ratio – Phase III, 20 percent RH at 73.4 F.

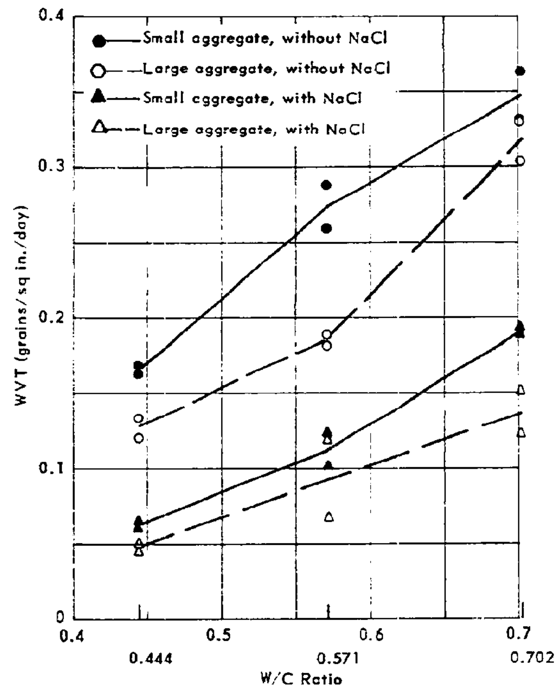

Figure 8b. WVT versus W/C ratio – Phase III, 50 percent RH at 73.4 F.

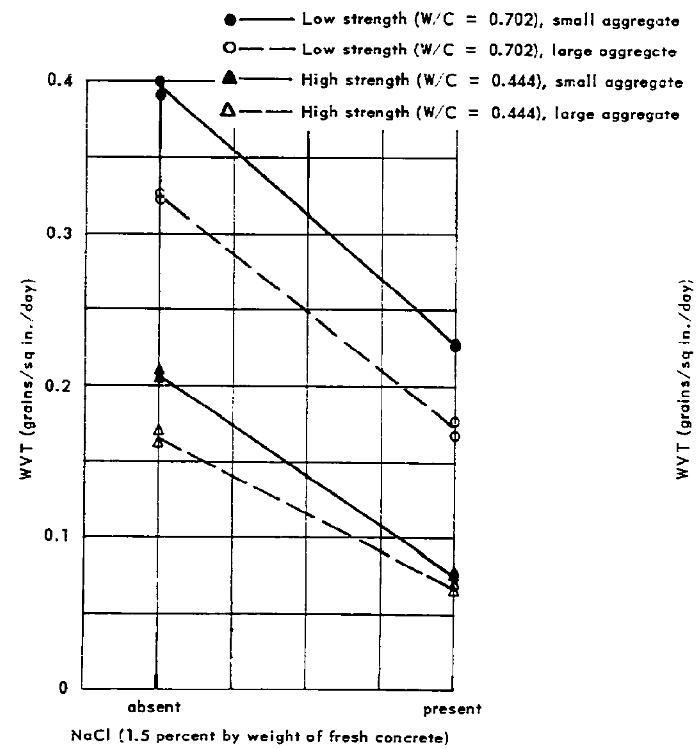

Figure 9a. WVT versus NaCl content - Phase III, 20 percent RH at 73.4 F.

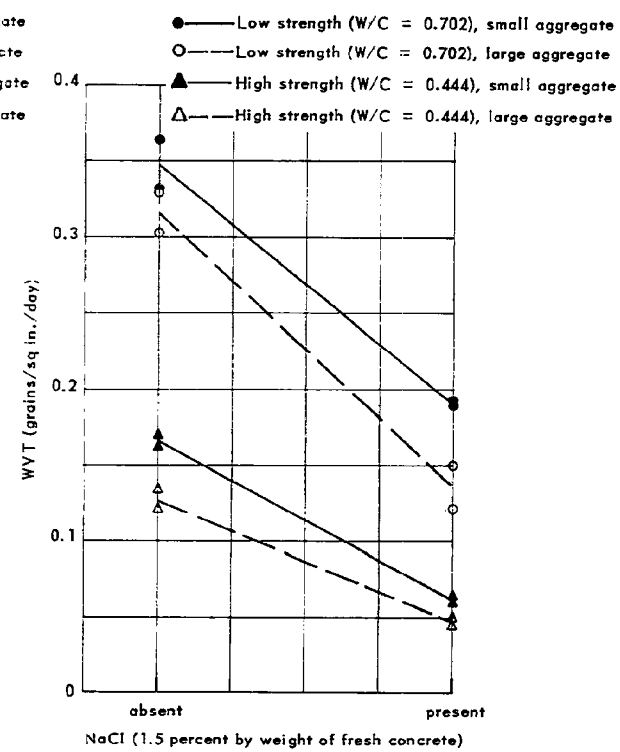

Figure 9b. WVT versus NaCl content - Phase III, 50 percent RH at 73.4 F.

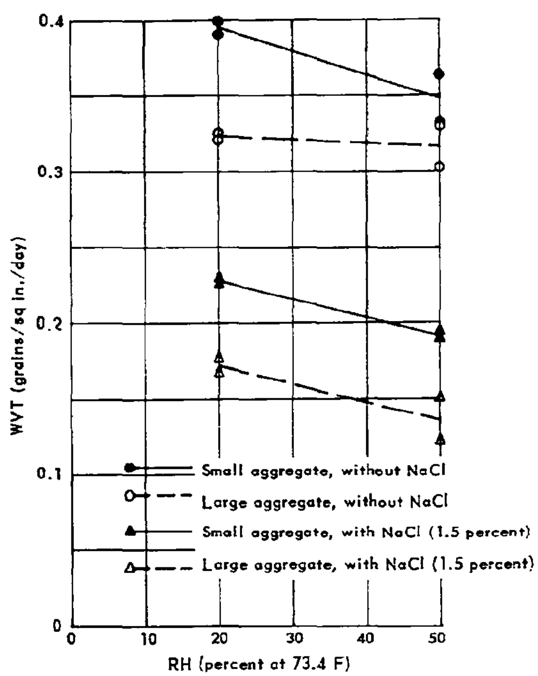

Figure 10a. WVT versus RH - Phase III, low strength (W/C = 0.702).

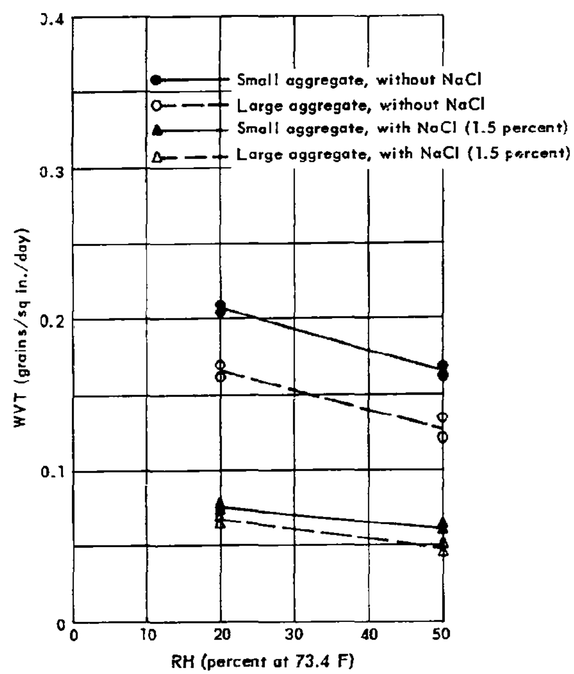

Figure 10b. WVT versus RH - Phase III, high strength (W/C = 0.444).

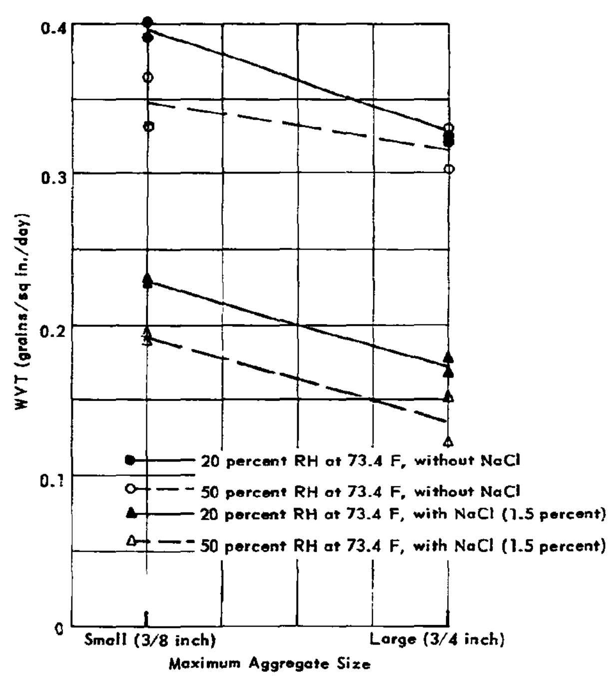

Figure 11a. WVT versus maximum aggregate size – Phase III, low strength (W/C = 0.702).

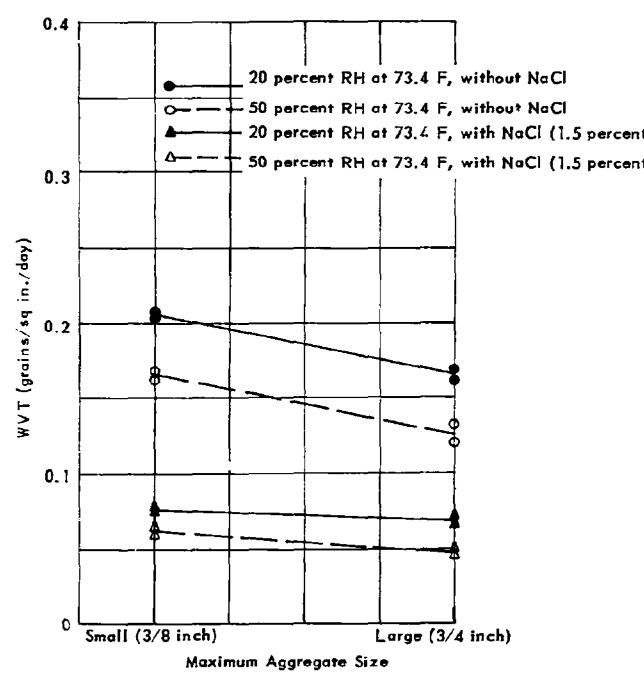

Figure 11b. WVT versus maximum aggregate size – Phase III, high strength (W/C = 0.444).

Compressive Strength. The results of the compressive-strength tests of Phase III are presented in Table V. Each value in Table V represents the average of three tests on 4-inch-diameter by 8-inch cylinders fog cured for the entire time prior to testing.

The compressive strengths of all of the concrete cylinders (not the average compressive strengths of Table V) were subjected to a regression analysis. The analysis is presented in Appendix D. A t-distribution test was used to determine the significance of the parameters of the regression equation and is presented in Table XIII in Appendix D. Table XIII shows that W/C ratio, NaCl, oleic acid, W/C ratio - NaCl interaction, and NaCl - oleic acid interaction are highly significant, and that W/C ratio - aggregate size interaction and W/C ratio - oleic acid interaction are significant. Aggregate size, aggregate size - NaCl interaction, and aggregate size - oleic acid interaction are not significant. A point of particular interest is the fact that the aggregate size is not significant but the W/C ratio - aggregate size interaction is significant. Some question arose when the analysis did not show aggregate size to be a significant variable. It is possible that large variations in the data obscured the effect of aggregate size. As an example, the data for concrete with W/C = 0.571, without NaCl and without oleic acid, did show that concrete with large aggregate had higher compressive strengths than concrete with small aggregate; however, the compressive-strength variation between maximum and minimum values for the two small-aggregate batches (supposedly identical batches) at an age of 78 weeks was 920 psi. Many other examples of large variations in the data were observed. These large variations in the data would tend to confound the effect of aggregate size (i.e., aggregate size would not appear as a statistically significant factor). It should be noted that two of the variables (type of steel and RH) of the WVT study are not present in the compressive-strength study.

As was done in the WVT study of Phase III, a graphical analysis was used to determine the manner in which the significant variables affect compressive strength. The compressive strength values of Table V are presented graphically in Figures 12, 13, 14, 15, 16, and 17.

Figure 12 shows that, for high-strength (W/C = 0.444) and low-strength (W/C = 0.702) concrete with and without NaCl, as time increases, compressive strength increases. Compressive strength increases rapidly during the first few weeks and slowly thereafter. This relationship has been well established by many tests and might be termed a classic relationship. The curves of Figure 12 are of the form:

$$\text{Compressive Strength} = (\text{Asymptotic Compressive Strength}) \left[1 - e^{-k(t - t_0)}\right]$$

and were fitted by the method of least squares. The fitting procedure is discussed in Appendix D. These curves indicate that after several months have elapsed (3 months or more), the compressive strength approaches an absolute maximum or asymptotic compressive strength. The asymptotic compressive strengths were calculated (see Appendix D) and are presented in Table V. These asymptotic compressive strengths will be discussed in connection with Figure 17.

Figure 12 shows that, for high- and low-strength concrete, adding NaCl (1.5 percent by weight of fresh concrete) decreases the compressive strength. However, the addition of the NaCl does not fundamentally alter the shape of the curves. The compressive-strength values of Table V could be presented in a figure, identical to Figure 12, but with and without oleic acid (instead of with and without NaCl). This figure would show that the effects of oleic acid are the same as the effects of NaCl; therefore, the figure is omitted.

Figure 13 shows much more clearly than Figure 12 that adding NaCl (1.5 percent by weight of fresh concrete) decreases the compressive strength. Figure 13 further shows that there is an interaction between the W/C ratio and NaCl (i.e, adding NaCl produces a greater net decrease in compressive strength for concrete with W/C = 0.444 than for concrete with W/C = 0.702).

Figure 14 shows that adding oleic acid decreases the compressive strength and that there is an interaction between the W/C ratio and oleic acid (i.e., adding oleic acid produces a greater decrease in compressive strength for concrete with W/C = 0.444 than for concrete with W/C = 0.702). It is interesting to note that Figures 13 and 14 show that the effects produced by adding oleic acid are almost identical to the effects produced by adding NaCl.

Figure 15 shows that, for large and small aggregate with and without NaCl, increasing the W/C ratio greatly decreases the compressive strength. Again, this relationship has been well established by many tests and might be termed a classic relationship. Furthermore, Figure 15 shows that there is a definite interaction between W/C ratio and maximum aggregate size. For W/C = 0.444, the data suggests that concretes with small aggregate have <u>higher</u> compressive strengths than concretes with large aggregate. However, for W/C = 0.571 and W/C = 0.702, the data also suggests that concretes with small aggregate have <u>lower</u> compressive strength than concretes with large aggregate. Figure 16 shows that when NaCl is replaced with oleic acid, the effects of W/C ratio and maximum aggregate size remain the same.

Table V. Experimental and Asymptotic Compressive Strength - Phase III

Batch No.	Experimental Compressive Strength[a]					Asymptotic Compressive Strength[b]
	2 Weeks	4 Weeks	26 Weeks	52 Weeks	78 Weeks	
SSL-1	3880	4360	4780	4810	4940	4840
SSL-2	3450	3820	4120	4080	4160	4120
SSL-3	3290	3560	4110	4060	4180	4120
SSL-4	3290	3590	4000	4190	4420	4450
SSL-5	4290	4780	5140	5060	5270	5160
SSL-6	3520	3790	4140	4150	4300	4200
SSL-7	3310	3630	3910	4080	4200	4190
SSL-8	3470	3700	4210	4570	4670	4750
SSL-9	3820	4290	4660	4550	4780	4660
SSL-10	3500	4050	4340	4320	4510	4390
SSL-11	3240	3520	4070	4180	4240	4190
SSL-12	3530	3780	4220	4300	4580	4570
SSL-13	3900	4430	5110	5170	5040	5110
SSL-14	3560	3830	4310	4370	4370	4360
SSL-15	3160	3540	4220	4370	4570	4500
SSL-16	3300	3750	4380	4720	4740	4760
SSM-1	5370	5960	6470	6520	6700	6560
SSM-2	4590	5030	5470	5260	5530	5420
SSM-3	4520	4920	5290	5460	5680	5670
SSM-4	4760	5090	5190	5550	5620	5450
SSM-5	5740	6170	6950	6940	7210	7040
SSM-6	4720	5000	5850	5720	6030	5880
SSM-7	4570	4470	5470	5650	5720	5740
SSM-8	4600	4800	5510	5810	5730	5780
SSM-9	5000	5460	5940	6090	5920	5990
SSM-10	4890	5080	5490	5390	5600	5500
SSM-11	4320	4700	5180	5510	5670	5730
SSM-12	4450	4820	5290	5580	5640	5660
SSM-13	5580	5990	6770	6940	7150	7080
SSM-14	4690	4940	5540	5570	5600	5580
SSM-15	4490	4850	5420	5870	5940	6030
SSM-16	4750	5050	5530	5610	5840	5770

Table V. Experimental and Asymptotic Compressive Strength - Phase III (Cont'd)

Batch No.	Experimental Compressive Strength[a]					Asumptotic Compressive Strength[b]
	2 Weeks	4 Weeks	26 Weeks	52 Weeks	78 Weeks	
SSH-1	6850	7380	8030	8590	9230	10370
SSH-2	5370	6000	6510	6690	7400	8250
SSH-3	5540	6100	6530	6370	7050	7280
SSH-4	6150	6660	7340	7250	7680	7420
SSH-5	6760	7380	7970	8220	8720	8840
SSH-6	5620	6250	6650	7110	7520	8010
SSH-7	5650	6020	6280	6530	6580	6460
SSH-8	5710	6240	6480	6810	6910	6730
SSH-9	6580	7230	7970	8060	8670	8610
SSH-10	6510	6970	7120	7620	8350	9310[c]
SSH-11	5770	6090	6890	6460	6600	6650
SSH-12	5960	6500	6870	7220	7090	7060
SSH-13	6720	7630	8130	8320	8150	8200
SSH-14	6100	6340	6640	7070	7750	8250[c]
SSH-15	5750	6050	6200	6440	6730	8090
SSH-16	5930	6320	6800	6910	6650	6790

a/ Pounds per square inch. Each value represents the average of 3 tests on 4-inch-dia. by 8-inch cylinders fog cured at 73.4 F for the entire period prior to testing.

b/ Pounds per square inch. Calculated (see Appendix E).

c/ Estimated.

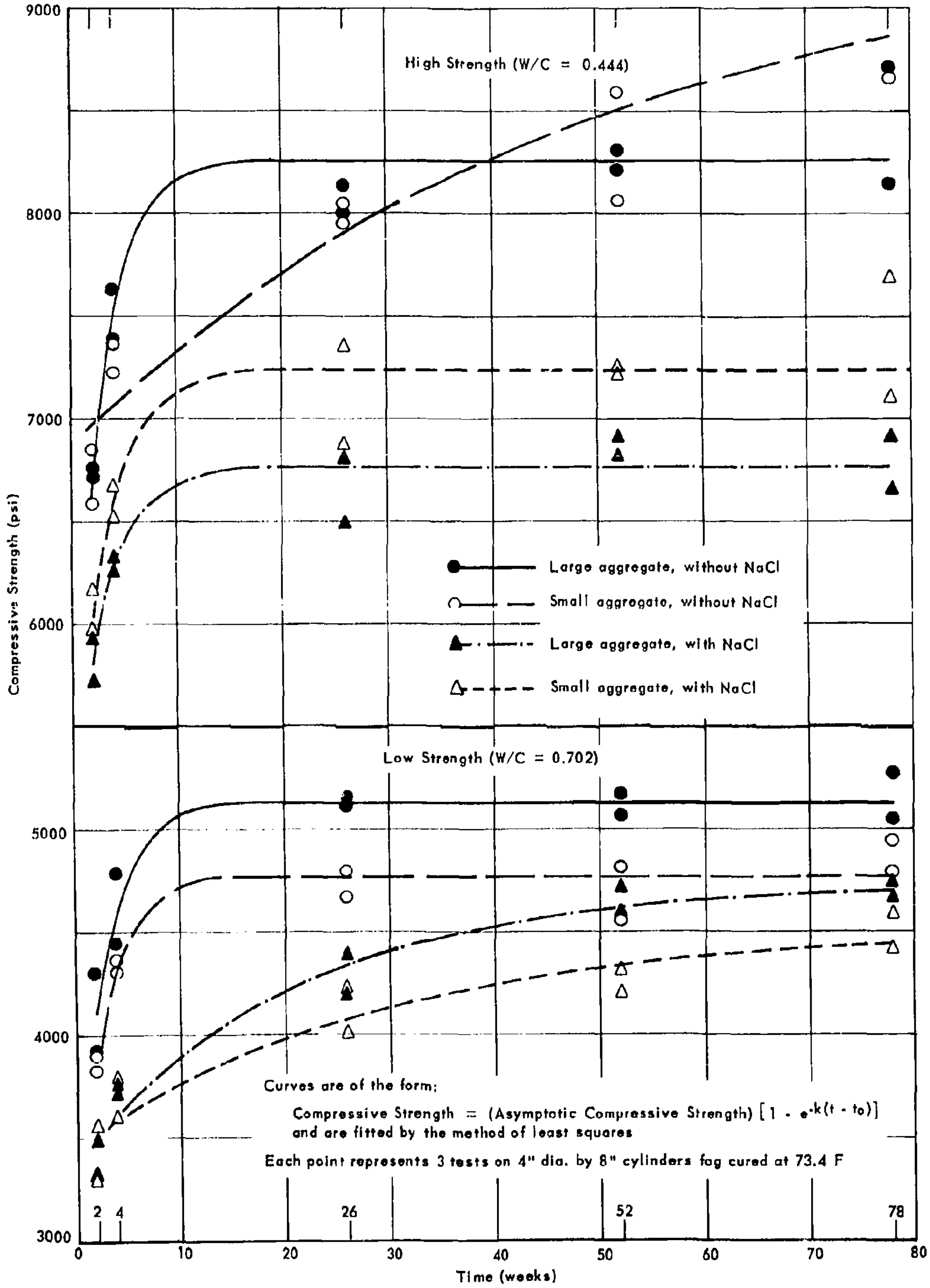

Figure 12. Compressive strength versus time - Phase III.

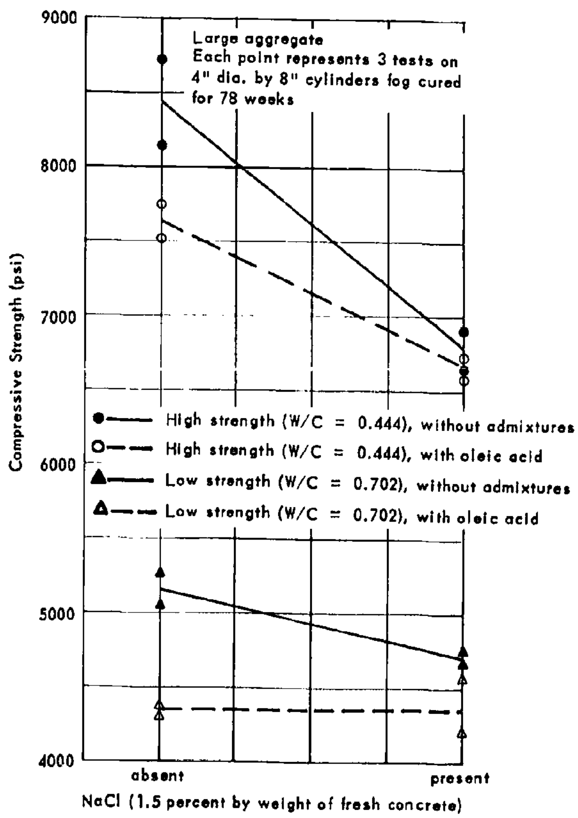

Figure 13. Compressive strength versus NaCl content - Phase III.

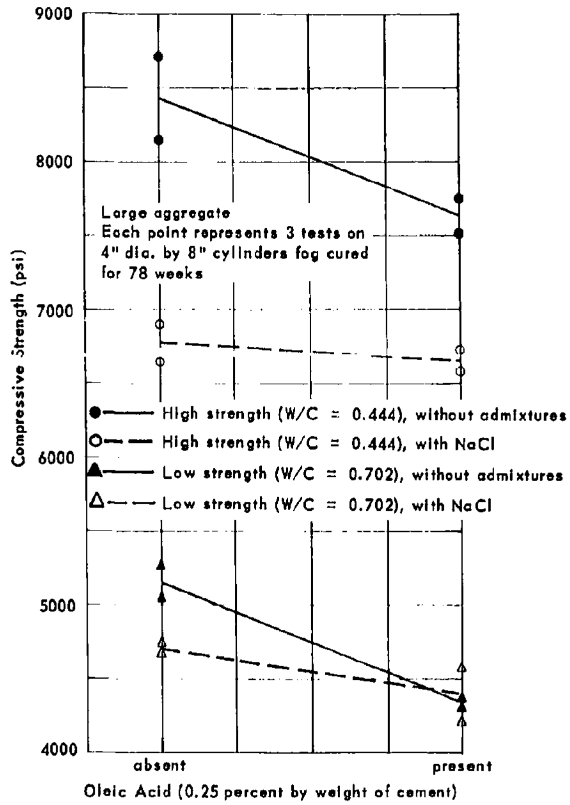

Figure 14. Compressive strength versus oleic acid content - Phase III.

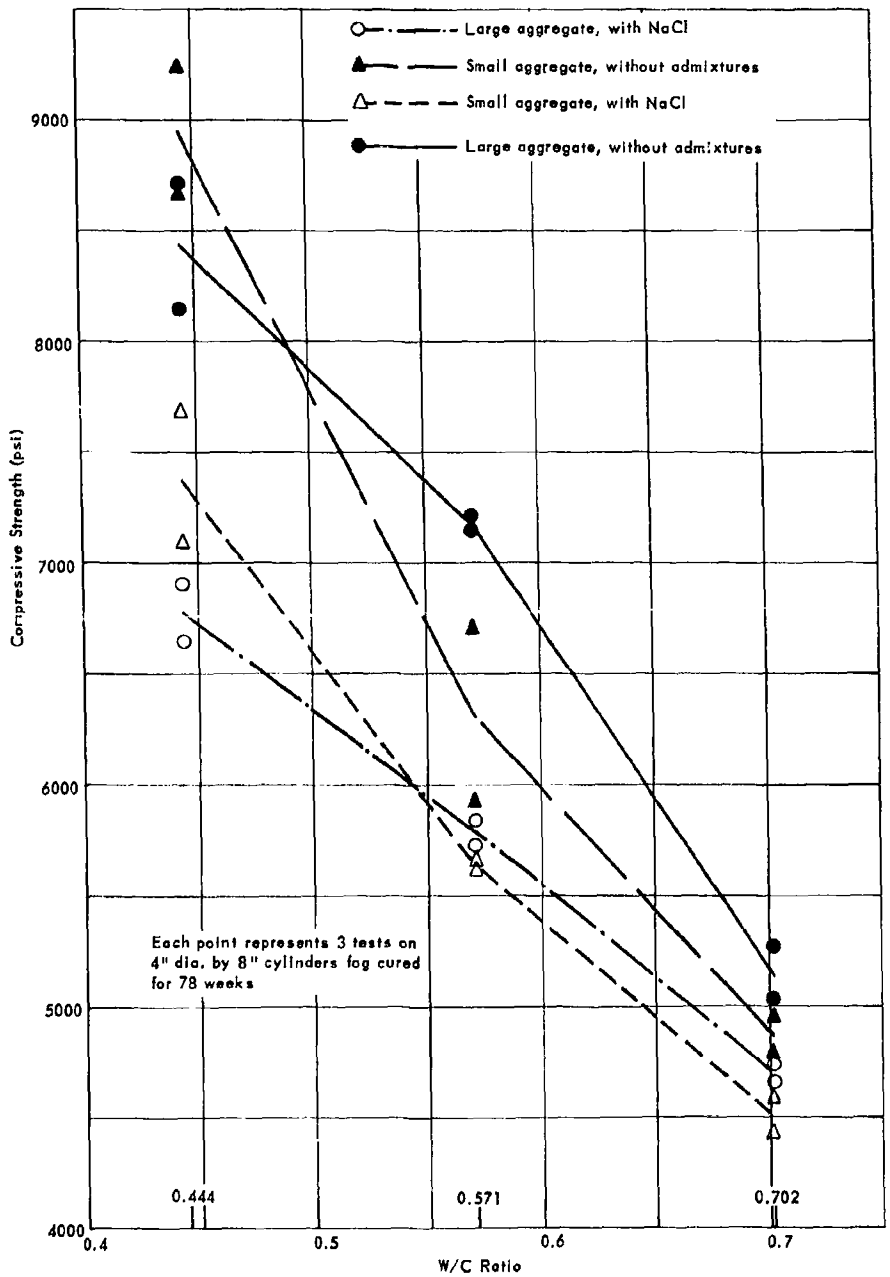

Figure 15. Compressive strength versus W/C ratio - Phase III, with and without NaCl.

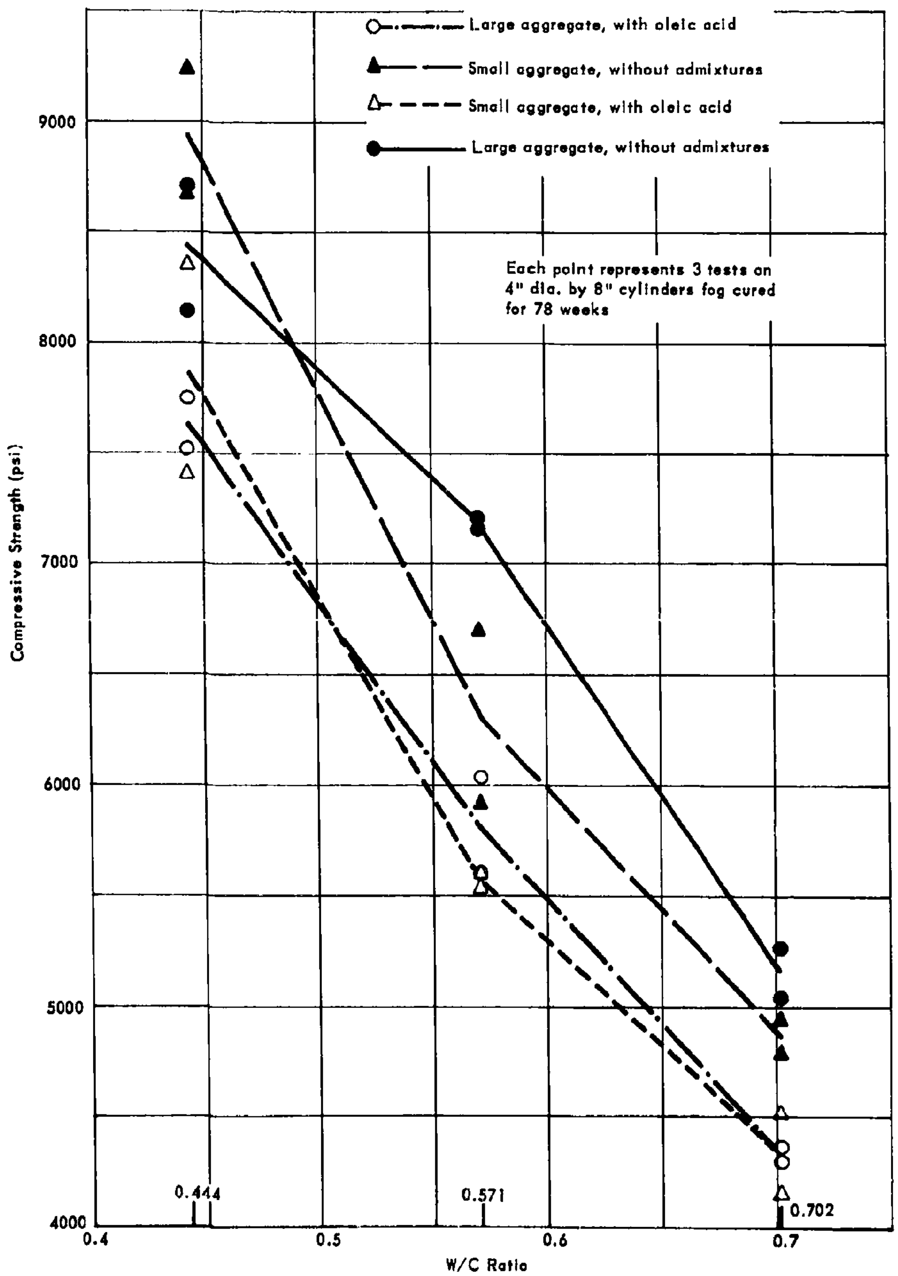

Figure 16. Compressive strength versus W/C ratio - Phase III, with and without oleic acid.

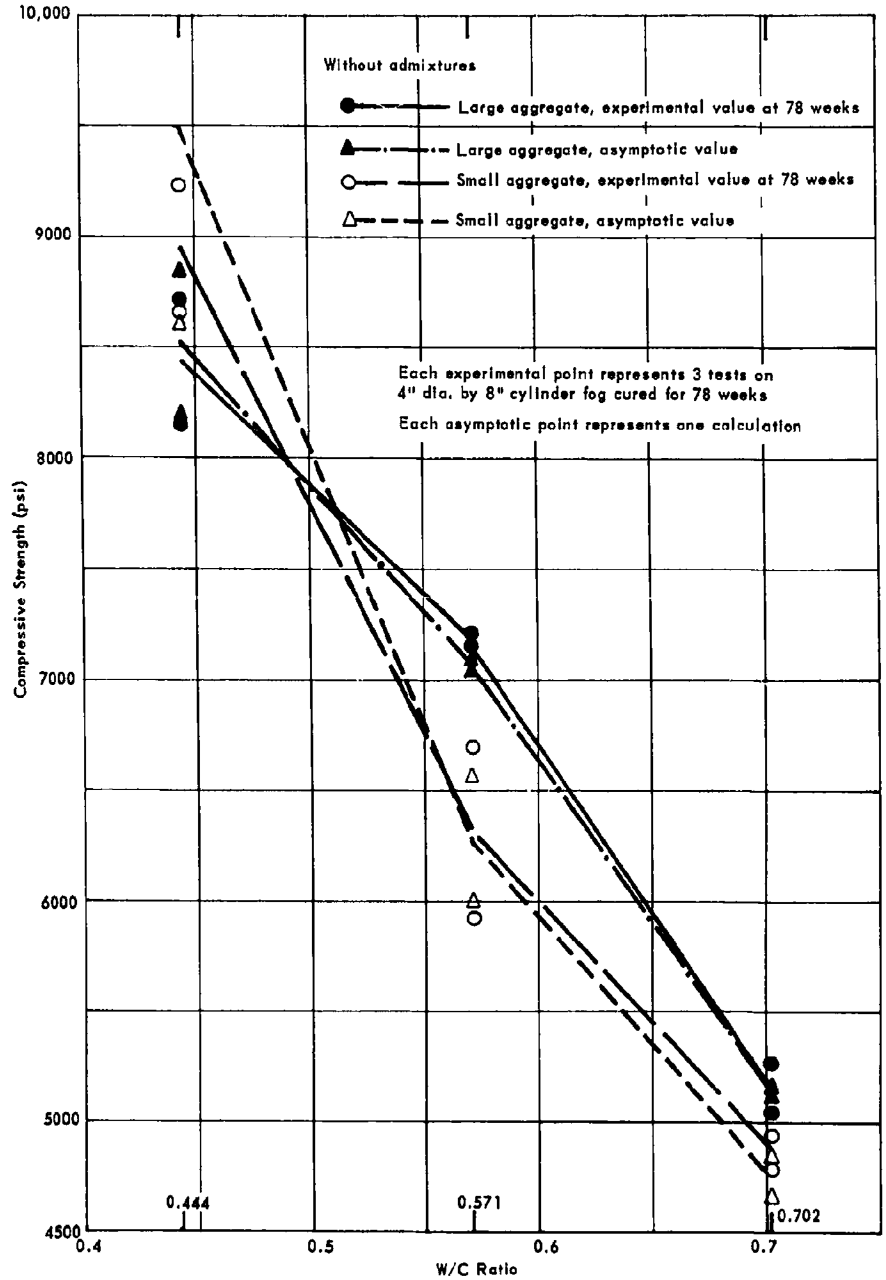

Figure 17. Experimental and asymptotic compressive strength versus W/C ratio - Phase III.

Figure 17 shows that, for large and small aggregate without NaCl and oleic acid, the asymptotic compressive strength agrees very closely with the experimental compressive strength at an age of 78 weeks. This close agreement seems to indicate that by an age of 78 weeks (1-1/2 years) the concrete has nearly reached maximum compressive strength. The compressive strength versus time curves of Figure 12 indicate that actually concrete with W/C = 0.702 reaches maximum compressive strength before an age of 78 weeks while concrete with W/C = 0.444 reaches maximum compressive strength after an age of 78 weeks. Figure 17 indicates that the calculated asymptotic compressive strength is a good prediction of the maximum (or ultimate) compressive strength. The same results were obtained for concretes with NaCl and oleic acid.

Sodium Chloride Whisker Crystals

Sodium chloride crystal growth (whiskers) on the concrete of Phases I and II was reported in Reference 2. The whiskers were observed to be growing on concrete specimens in wet cups, and only on concrete made with mixing water containing NaCl. The water placed in the bottom of the wet cups was tap water; therefore, the whiskers must consist almost exclusively of NaCl that was added to the concrete at the time of mixing.

Whiskers have been observed on concrete specimens in wet cups of Phase III (Figures 18 and 19). The whiskers of Phase III have the same physical characteristics as those of Phases I and II, described on page 33 of Reference 2.

The strength of the concrete definitely affects the growth of the whiskers. Whiskers have been observed to grow in large quantities on all low-strength (W/C = 0.702) and medium-strength (W/C = 0.571) concrete specimens which contain NaCl. These whiskers appeared within a few days after the specimens were placed in the wet cups. A larger quantity of whiskers appear on the low-strength concrete, but the difference between the quantity on the low-strength concrete and the quantity on the medium-strength concrete is small. The whiskers on the low-strength concrete are finer and longer than those on the medium-strength concrete. However, whiskers have been observed to grow only in very small quantities on high-strength concrete specimens which contain NaCl. These whiskers did not appear until the specimens had been in the wet cups for several months. From the above observations it can be seen that as strength is increased, whisker growth is decreased.

Figure 18. Typical NaCl whisker crystal growth on concrete specimen in a wet cup.

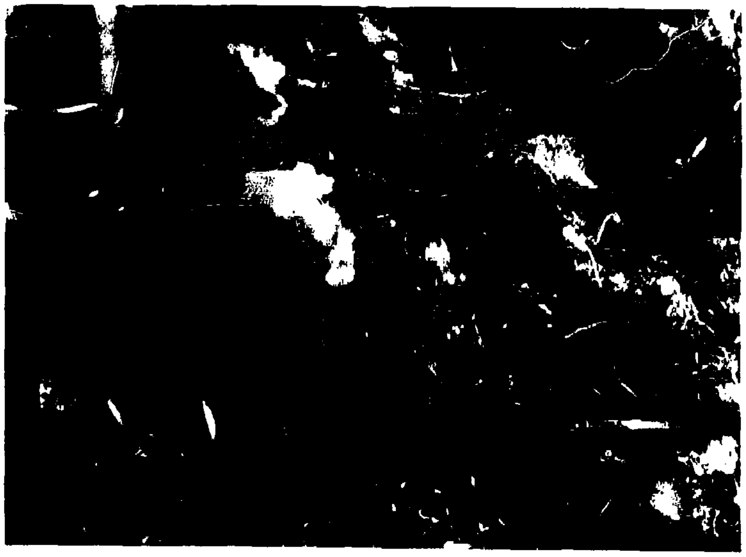

Figure 19. Typical NaCl whisker crystal growth magnified.

Whiskers appear to grow in somewhat larger quantities on concrete in 20 percent RH at 73.4 F than on concrete in 50 percent RH at 73.4 F. The difference between quantities is not large and appears to be of about the same order of magnitude as the difference between the WVT rates of concrete in 20 and in 50 percent RH at 73.4 F. This similarity of differences suggests that the NaCl may migrate with the water through the concrete.

As far as can be observed, the other variables (type of steel, maximum aggregate size, and oleic acid) do not have a significant effect on whisker growth.

In order to further investigate the possibility that the NaCl migrates with the water through the concrete, a special wet cup was constructed. The concrete was made with tap water and therefore contained practically no NaCl. It had a W/C ratio of 0.702, large aggregate, no steel, and no oleic acid. A 4-inch-diameter cylinder was cast and a 2-inch-thick disk was cut from the cylinder and placed in a wet cup. The wet cup was completely filled with a saturated solution of NaCl and placed in the environment of 20 percent RH at 73.4 F. The cup was designed so that the bottom of the concrete disk would project 1 inch down into the solution of NaCl. It was thought that if the NaCl migrates with the water through concrete, then eventually the NaCl in the solution would migrate up through the concrete and form whiskers on the top surface. However, as of this writing, no whiskers have appeared after 500 days. For the 500-day period the WVT was 0.099 grains per square inch per day. At the time of mixing, the concrete of the special wet cup was comparable to wet cup S148 of Phase III. Wet cup S148 had a WVT rate of 0.326 grains per square inch per day, which is much higher than the WVT rate of the special wet cup. Apparently the NaCl in the special wet cup has entered the concrete in sufficient quantities to reduce the WVT. The absence of whiskers will not be used as the basis for any conclusions at the present time. The test will be continued. It is possible that the NaCl migration is very slow and years may be required for it to migrate through the 2 inches of concrete in the special wet cup.

Part 2. WATER VAPOR TRANSMISSION OF AGGREGATES

EXPERIMENTAL PROCEDURE

In order to further investigate the effect of the aggregate on the WVT rate of concrete, WVT rates were determined for San Gabriel (SG) and Guam reef coral (GMR) aggregates.

San Gabriel Rock

Eight large rocks were obtained from the Irwindale (California) Pit of the Consolidated Rock Company. Several cores 4 inches in diameter were drilled from the rocks at different angles to the fabric plane (fabric is the orientation in space of the crystals of which a rock is composed), and disks of two thicknesses, 1-1/2 and 3 inches, were sawed from the cores. These disks were subjected to megascopic and petrographic analyses and classification and then sealed in wet cups identical to those used for the concrete disks. The wet cups were placed in an ambient environment of 20 percent RH at a temperature of 73.4 F. They were weighed every 2 weeks and the weight losses were determined. Graphs of weight loss versus time were drawn for all of the wet cups. The experiment has been in progress for approximately 1 year.

Guam Reef Coral

Two 4-inch-diameter cores were obtained from Guam. One core was from the Tarague Beach area and the other from Cabras Island. Upon arrival at NCEL, two 3-inch-thick disks were cut from each core and placed in wet cups, which thereafter were treated in the same manner as the SG wet cups. The experiment has been in progress for nearly 1 year.

ANALYSIS AND CLASSIFICATION

San Gabriel Rock

The orientation and quality of the metamorphic fabric of the SG cores was determined by megascopic analysis. The results of the analysis are presented in Part A of Appendix E. The development of fabric in these cores ranges from well-developed banding in the gneisses in part of Group G to the apparent absence of fabric in Group C. Some of the groups show well-developed fabric planes while others show only linear elements which have at best poorly developed planar features. In all of the groups except Group C the fabric plane was observed and recorded as a plane with its orientation referred to the cylindrical axis of the core (i.e., a core taken perpendicular to the fabric plane inclined 90 degrees to the cylindrical axis, and a core taken parallel to the fabric plane would have the fabric plane inclined zero degrees to the cylindrical axis).

A petrographic analysis and classification of the eight San Gabriel rocks was made and the results are presented in Part B of Appendix E. For the purpose of rock classification a rough estimate of the amount of the various minerals is generally sufficient. A thin section is viewed under the microscope and the fourfold division of the field by the cross hairs is used to estimate the relative area occupied by the various minerals in each of the four quadrants. This operation is repeated so as to cover the entire thin section, thereby offering a fairly representative average for computation. Since the volume is directly proportioned to the area, a good estimate of the percentage of each mineral present can be made (see Reference 6).

Guam Reef Coral

GMR is described in Military Geology of Guam, Mariana Islands, 1959, as "Compact Caralline Limestone: Massive, compact, recrystallized, white to light brown limestone containing numerous coral heads in a hard, fine-grained algal matrix. Excavation requires extensive drilling and blasting."

DISCUSSION OF RESULTS

San Gabriel Rock

As discussed above, WVT rates for SG were determined from the slopes of the graphs of weight loss versus time, using the formula WVT = $(W/t)C_A$. The WVT rates of a 300-day period (from 100 to 400 days age) are presented in Table VI. The WVT rates of Table VI are plotted as a bar graph in Figure 20.

In Figure 20 the angle of inclination of the fabric plane of each specimen is indicated. It might be expected that the more nearly parallel the fabric plane is to the direction of flow (i.e., the smaller the angle of inclination) the higher the WVT rate would be. In general this is shown to be true; however, there are two groups (out of eight groups) that provide exceptions. In Group D two specimens with equal angles of inclination (85 degrees) have quite different WVT rates, one being nearly twice the other. In Group G, containing four specimens, a random pattern exists; two specimens with equal angles of inclination (10 degrees) have the highest and lowest WVT rates. Apparently WVT is not a simple function of the angle of inclination of the fabric plane.

Table VI. WVT of SG

Group Symbol	Cup No.	I a/	Inclination of Fabric Plane b/	W/t c/	WVT d/	Average WVT e/
A	U737	3.04	5	0.0738	0.102	—
A	U738	1.55	72	0.0402	0.056	—
A	U739	3.03	65	0.0517	0.072	0.077
B	U602	3.03	40	0.0716	0.099	—
B	U603	1.54	40	0.0708	0.098	—
B	U604	1.43	87	0.0633	0.087	0.095
C	U857	3.02	—	0.0195	0.027	—
C	U858	1.52	—	0.0258	0.036	0.032
D	U859	3.08	85	0.0375	0.052	—
D	U860	1.52	85	0.0487	0.068	0.060
E	U861	3.05	40	0.0972	0.135	—
E	U862	1.54	40	0.0831	0.115	0.125
F	U863	1.60	10	0.0490	0.068	—
F	U864	3.04	5	0.0582	0.081	0.075
G	U865	1.52	10	0.0574	0.080	—
G	U866	2.99	10	0.0390	0.054	—
G	U867	1.53	80	0.0465	0.065	—
G	U868	3.00	75	0.0444	0.062	0.065
H	U869	1.52	45	0.127	0.176	—
H	U870	2.98	45	0.131	0.181	0.179

a/ Length of flow path (thickness of disk), inches.

b/ Angle of inclination of fabric, measured from vertical (axis of disk), degrees.

c/ Slope of graph of weight loss versus time, grams per day.

d/ WVT = $(W/t)C_A$ (for 4-inch-dia. disk, C_A = 1.388), grains per square inch per day. For a 400-day period (100-500 days age).

e/ Average for each group.

Note: 20 percent RH at 73.4 F.

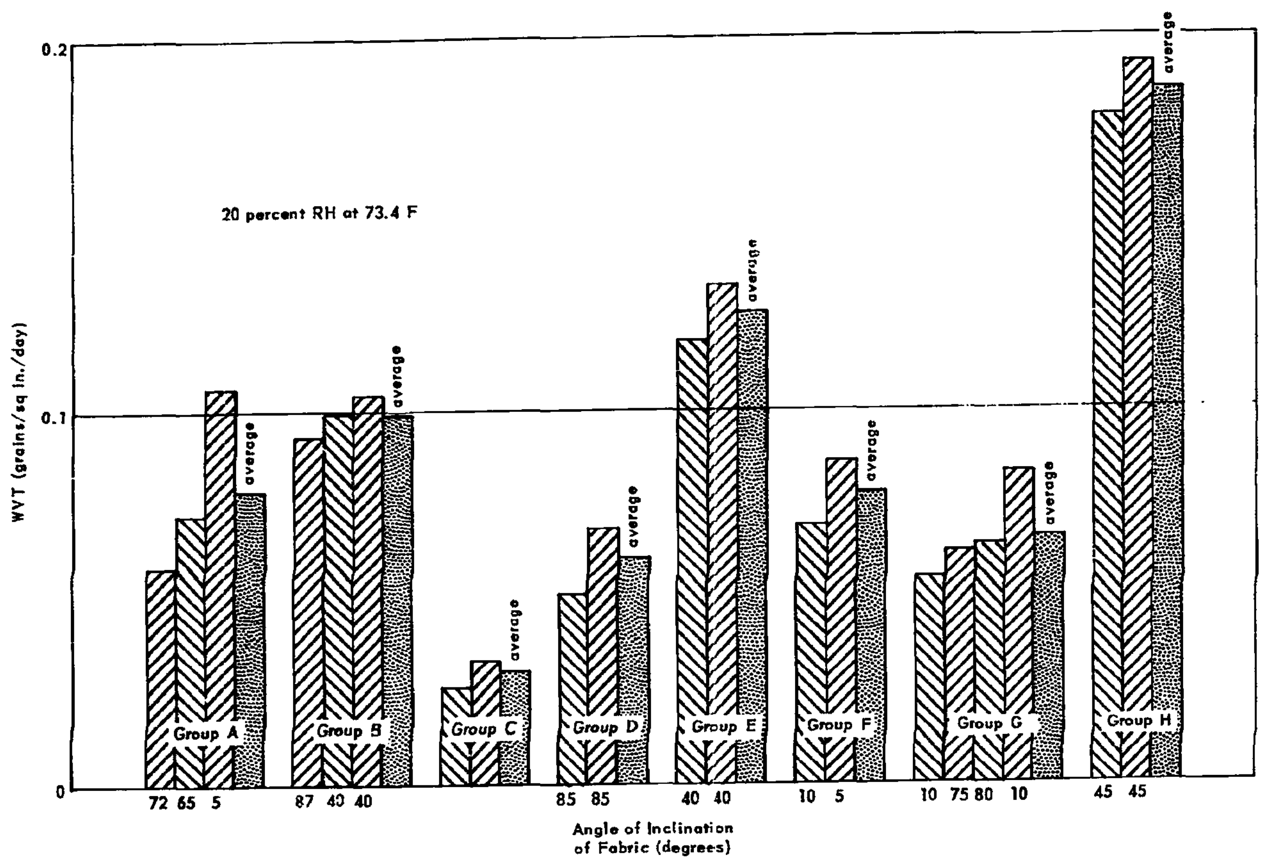

Figure 20. Bar graph of WVT for each SG group.

Since the angle of inclination did not appear to be significant, the average WVT for each group was also plotted in Figure 20. The range of average WVT rates for the SG is 0.030 to 0.186 grains per square inch per day. The range of WVT rates for the concrete of Phase III was 0.045 to 0.401 grains per square inch per day (see Table IV). Although the WVT rates of SG are somewhat lower than the WVT rates of concrete, they are still of the same order of magnitude (i.e., the largest value for concrete is less than 10 times the smallest value for concrete, and the same holds true for SG rock). The small difference between the WVT rates of SG and of concrete may explain why different aggregate sizes had only a small effect on the WVT rates in Phase III. However, the difference between the WVT rates of SG and the WVT rates of concrete is large enough to indicate that most of the WVT occurs through the mortar and not through the aggregate.

Guam Reef Coral

As was done for SG, WVT rates for GMR were determined from the slopes of the graphs of weight loss versus time using the formula WVT = $(W/t)C_A$. The WVT rates for a 250-day period (from 100 to 350 days age) are presented in Table VII.

Table VII. WVT of GMR

Origin of Coral a/	Cup No.	l b/	W/t c/	WVT d/
Tarague Beach, Guam, M. I.	599A	3.03	0.0824	0.114
Tarague Beach, Guam, M. I.	599B	2.99	0.0778	0.108
Cabras Island, Guam, M. I.	600A	2.99	0.0888	0.123

a/ Site from which cores were taken.

b/ Length of flow path (thickness of disk), inches.

c/ Slope of graph of weight loss versus time, grams per day.

d/ WVT = $(W/t)C_A$ (for 4-inch-dia. disk, C_A = 1.388), grains per square inch per day. For a 250-day period (100-350 days age).

Note: 20 percent RH at 73.4 F.

The range of WVT rates for GMR is 0.108 to 0.123 grains per square inch per day. In Reference 1 the range of WVT rates for concrete made with GMR was 0.326 to 0.343 grains per square inch per day. This comparison closely resembles the comparison for SG. Although the WVT rates of GMR are somewhat lower than the WVT rates of concrete, they are still of the same order of magnitude.

Part 3. SUMMARY

FINDINGS AND CONCLUSIONS

Water Vapor Transmission

1. An equation of the form WVT = W/tA is more suitable for the observed phenomenon than an equation of the form WVT = Wl/tA.

2. WVT decreases with increase in age of concrete.

3. WVT decreases with an increase in strength of concrete (decrease in W/C ratio).

4. WVT decreases with an increase in maximum aggregate size.

5. WVT decreases with the presence of NaCl (1.5 percent by weight of fresh concrete).

6. WVT appears to decrease with an increase in RH (from 20 to 50 percent at 73.4 F). However, since deposits of salts were observed on specimens in the 50-percent RH environment, the significance of the apparent affect of RH is doubtful.

7. WVT is independent of either type of steel contained in the concrete.

8. WVT is independent of the presence of oleic acid.

Compressive Strength

1. Compressive strength is decreased by an increase in W/C ratio.

2. Compressive strength is decreased by the presence of 1.5 percent NaCl in the concrete.

3. Compressive strength is decreased by the presence of 0.25 percent oleic acid in the concrete.

4. Compressive strength appears to be independent of maximum aggregate size (for 3/8-inch and 3/4-inch maximum aggregate sizes).

5. Compressive strength is affected by a W/C ratio - maximum aggregate size interaction (e.g., at W/C = 0.444, the data suggest that compressive strength is decreased by an increase in maximum aggregate size; whereas, at W/C = 0.702, the data suggest that compressive strength is increased by an increase in maximum aggregate size).

Sodium Chloride Whisker Crystals

1. Whiskers grow only on concrete specimens which contain NaCl.

2. The amounts of whiskers are larger on lower strengths of concrete.

Statistical Design and Analysis

Statistically designed and analyzed quarter- and half-replicate experiments were used successfully to determine WVT rates, thereby reducing the required number of specimens.

RECOMMENDATIONS

1. The ranges of the significant variables (W/C ratio, maximum aggregate size, RH, and absence or presence of sea-water salts) should be expanded in order to determine the limiting values, if any, of the WVT of concrete.

2. It has become apparent to the authors that if the investigation of WVT is to be carried much further, a better understanding of the physical mechanisms of WVT must be realized. Toward this end, experiments need to be devised to determine the physical mechanisms of WVT.

3. Further studies to correlate electrical resistivity of concrete to corrosiveness of embedded steel should be made. Such a correlation, if any exists, should lead to the development of a simple test to determine the degree of corrosiveness to steel of any concrete environment.

ACKNOWLEDGMENT

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REFERENCES

1. U. S. Naval Civil Engineering Laboratory. Technical Report R-217, The Effect of Salt in Concrete on Compressive Strength, Water Vapor Transmission, and Corrosion of Reinforcing Steel, by D. F. Griffin and R. L. Henry. Port Hueneme, California, 12 November 1962.

2. U. S. Naval Civil Engineering Laboratory. Technical Report R-130, Water Vapor Transmission of Plain Concrete, by D. F. Griffin and R. L. Henry. Port Hueneme, California, 16 May 1961.

3. Griffin, D. F., and R. L. Henry. "Integral Sodium Chloride Effect on Strength, Water Vapor Transmission, and Efflorescence of Concrete," Journal of ACI, Vol. 58, No. 6, December 1961, pp. 751-772.

4. National Academy of Sciences-National Research Council Publication 596, Building Research Advisory Board Report 14 to the Federal Housing Administration, "Effectiveness of Concrete Admixtures in Controlling the Transmission of Moisture Through Slabs-on-Ground," edited by W. S. Brown. Washington, D. C., 1958.

5. Babbitt, J. D. "The Movement of Moisture Through Solids," ASTM Bulletin 212, February 1956, pp. 58-60.

6. Wahlstrom, E. E. Igneous Minerals and Rocks. John Wiley & Sons, New York, 1947, pp. 3, 256-7.

Appendix A

SUMMARY OF CONCRETE MIX DESIGN DATA

A. Characteristics of Materials

Cement: Victor, Type III
Aggregate: San Gabriel rock (SG)

Coarse: sp gr = 2.66; 24-hr abs = 1.6 percent
Fine: sp gr = 2.63; 24-hr abs = 1.8 percent
Grading:

Pounds Retained on Each Sieve for 2.25-Cu-Ft Batch

Sieve	3/4-Inch Max.			3/8-Inch Max.		
	H	M	L	H	M	L
3/4	7.4	7.8	6.2	0	0	0
3/8	74.1	75.5	73.7	0	0	0
No. 4	46.9	44.2	45.4	103.9	106.0	106.2
No. 8	27.2	28.6	32.2	38.3	39.4	39.8
No. 16	24.7	31.2	31.1	27.0	29.4	31.8
No. 30	27.2	28.6	31.3	23.6	24.1	23.7
No. 50	22.2	23.4	28.6	18.7	20.9	24.0
No. 100	12.4	13.0	14.6	18.4	19.8	21.0
Pan	5.0	7.8	7.0	17.2	18.4	19.2
Total	247.1	260.1	270.1	247.1	258.0	265.7

Note: H, M, L = high, medium, and low relative strengths.

Water: Port Hueneme tap water at 73.4 F

Chemical analysis (ppm): hydroxide (0.0); carbonate (0.0); bicarbonate (137.0); chlorides (62.0); calcium (38.0); magnesium (14.6); sulphate (465.0); sodium and potassium (219.0)

Slump: 3 inches (without additives)
Additives: Sodium chloride, U.S.P. granular; F.W. = 58.45 (1.5 percent by weight of plastic concrete unless otherwise noted); oleic acid, U.S.P. (0.25 percent by weight of cement)

B. Mix Designs (each batch 2.25 cu ft)

Aggregate: 3/4-inch maximum particle size
Sand: FM = 3.16

Mix	Cement (lb)	Water[a] (lb)	Cement Factor (sacks per cu yd)	W/C
H	59.50	26.4	7.62	0.444
M	46.25	26.4	5.92	0.571
L	37.60	26.4	4.81	0.702

Aggregate: 3/8-inch maximum particle size
Sand: FM = 2.95

Mix	Cement (lb)	Water[a] (lb)	Cement Factor (sacks per cu yd)	W/C
H	61.9	27.5	7.92	0.444
M	48.1	27.5	6.16	0.571
L	39.2	27.5	5.02	0.702

a/ The quantity of water added at the mixer was corrected for moisture present in the aggregate and moisture required for absorption.

Appendix B

EXPERIMENTAL DESIGN AND DATA ANALYSIS (WVT) - PHASE II (480-day period)

An experiment was designed to evaluate the effects of six possible factors on WVT rate through concrete; namely:

Strength of concrete	Low (A = -1), high (A = +1)
Position of slice from test cylinder	Bottom (B = -1), top (B = +1)
Maximum aggregate size	3/8 inch (C = -1), 3/4 inch (C = +1)
NaCl	Absence (D = -1), presence (D = +1)
Oleic acid	Absence (E = -1), presence (E = +1)
RH	20 percent (F = -1), 50 percent (F = +1)

The actual factor combinations consisted of a specified one-fourth of the possible 64 combinations, so arranged that the individual effects of each of the above factors could be separately estimated. For each factor, -1 indicates the "lower" level of the factor and +1 indicates the "upper" level. The quarter-replicate factorial design is shown in Table VIII.

The WVT values of Table II for the 480-day period (from 400 to 880 days age) were subjected to an analysis of variance which, together with the analysis for the 100-day period (from 80 to 180 days age) analyzed on page 42 of Reference 2 is presented in Table IX. Implied in the 480-day analysis is the linear statistical model for the expected WVT rate:

$$\text{"Expected" WVT Rate} = 0.182 - 0.070A + 0.020B - 0.0200 - 0.045D + 0.006E + 0.028F$$

Table VIII. Experimental Design - Phase II

Factor Combination	Factor Level					
	A	B	C	D	E	F
1	-1	-1	-1	-1	-1	-1
2	+1	+1	+1	-1	+1	-1
3	+1	+1	-1	-1	-1	+1
4	-1	-1	+1	+1	+1	+1
5	+1	-1	+1	+1	-1	-1
6	+1	-1	-1	-1	+1	+1
7	-1	+1	+1	-1	-1	+1
8	-1	+1	-1	+1	+1	-1
9	+1	+1	-1	-1	-1	-1
10	-1	-1	+1	-1	+1	-1
11	-1	-1	-1	+1	-1	+1
12	+1	+1	+1	+1	+1	+1
13	+1	-1	+1	-1	-1	+1
14	+1	-1	-1	+1	+1	-1
15	-1	+1	+1	+1	-1	-1
16	-1	+1	-1	-1	+1	+1

Table IX. Analysis of Variance (WVT) - Phase II

Period	Source of Variation	Degree of Freedom	Mean Square	F
100-Day	Strength of Concrete	1	0.2951	52.3
	Slice Position	1	0.0044	0.9
	Maximum Aggregate Size	1	0.0428	8.7
	NaCl	1	0.1620	32.7
	Oleic Acid	1	0.0001	0.0
	RH	1	0.0003	0.1
	Residual Error	9	0.0050	—
480-Day	Strength of Concrete	1	0.0795	30.6
	Slice Position	1	0.0062	2.4
	Maximum Aggregate Size	1	0.0067	2.6
	NaCl	1	0.0328	12.6
	Oleic Acid	1	0.0006	0.2
	RH	1	0.0128	4.9
	Residual Error	9	0.0026	—

Note: For both periods significance level of F with 1 and 9 degrees of freedom at the 5% level is 5.12, and at the 1% level is 10.56.

Appendix C

EXPERIMENTAL DESIGN AND DATA ANALYSIS (WVT) - PHASE III

An experiment was designed to evaluate the possible effects of six factors on the WVT rate through concrete; namely:

Strength of concrete	Low (A = -1), medium (A = 0), high (A = +1)
Type of steel	One type (B = -1), another type (B = +1)
Maximum aggregate size	3/8 inch (C = -1), 3/4 inch (C = +1)
NaCl	Absence (D = -1), presence (D = +1)
Oleic acid	Absence (E = -1), presence (E = +1)
RH	20 percent (F = -1), 50 percent (F = +1)

The actual factor combinations consisted of a specified one-half of the possible 96 combinations so arranged that the individual effects of each of the above factors could be separately estimated. For each factor, -1 indicates the "lower" level of the factor, +1 indicates the "upper" level, and, in the case of strength of concrete, 0 indicates the "middle" level. The half-replicate factorial design is shown in Table X.

The WVT values of Table IV were subjected to an analysis of variance, which is presented in Table XI.

Table X. Experimental Design - Phase III

Factor Combination[a]	Factor Level					
	A	B	C	D	E	F
SSL-1	-1	-1	-1	-1	-1	-1
SSL-2	-1	-1	-1	-1	+1	+1
SSL-3	-1	-1	-1	+1	+1	-1
SSL-4	-1	-1	-1	+1	-1	+1
SSL-5	-1	-1	+1	-1	-1	+1
SSL-6	-1	-1	+1	-1	+1	-1
SSL-7	-1	-1	+1	+1	+1	+1
SSL-8	-1	-1	+1	+1	-1	-1
SSL-9	-1	+1	-1	-1	-1	+1
SSL-10	-1	+1	-1	-1	+1	-1
SSL-11	-1	+1	-1	+1	+1	+1
SSL-12	-1	+1	-1	+1	-1	-1
SSL-13	-1	+1	+1	-1	-1	-1
SSL-14	-1	+1	+1	-1	+1	+1
SSL-15	-1	+1	+1	+1	+1	-1
SSL-16	-1	+1	+1	+1	-1	+1

a/ SSL: Low-strength concrete; therefore all A = -1.
SSM-1 through 16: Same as SSL-1 through 16 except medium-strength concrete; therefore all A = 0.
SSH-1 through 16: Same as SSL-1 through 16 except high-strength concrete; therefore all A = +1.

Table XI. Analysis of Variance (WVT) - Phase III

Source of Variation	Degree of Freedom	Mean Square	F	Significance Level of F
Main Effects				Significance level of F with 1 and 2 degrees of freedom at the 5% level is 4.35, and at the 1% level is 8.10
Strength of Concrete	2	0.0895645	239.99	
Type of Steel	1	0.0001203	0.32	
Maximum Aggregate Size	1	0.0286163	76.68	
NaCl	1	0.2326868	623.49	
Oleic Acid	1	0.0000030	0.08	
RH	1	0.0144908	38.83	
Interaction of Strength With Other Treatments				Significance level of F with 2 degrees of freedom at the 5% level is 3.49, and at the 1% level is 5.85
Strength - Steel	2	0.0000076	0.02	
Strength - Aggregate	2	0.0018576	4.98	
Strength - NaCl	2	0.0041452	11.11	
Strength - Oleic Acid	2	0.0002078	0.56	
Strength - RH	2	0.0002438	0.65	
Two-Factor Interactions for Two-Level Treatments				
Steel - Aggregate	1	0.0010830	2.90	Significance level of F with 1 and 2 degrees of freedom at the 5% level is 4.35, and at the 1% level is 8.10
Steel - NaCl	1	0.0003101	0.83	
Steel - Oleic Acid	1	0.0000053	0.00	
Steel - RH	1	0.0002521	0.68	
Aggregate - NaCl	1	0.0017521	4.69	
Aggregate - Oleic Acid	1	0.0004813	1.02	
Aggregate - RH	1	0.0006601	1.77	
NaCl - Oleic Acid	1	0.0002521	0.68	
NaCl - RH	1	0.0012813	3.43	
Oleic Acid - RH	1	0.0002001	0.54	

Appendix D

DATA ANALYSIS (COMPRESSIVE STRENGTH) - PHASE III

EXPERIMENTAL DESIGN

Appendix C shows the experimental design from which the compressive-strength study was made. The factors were:

Strength (S) of concrete:	Three levels
Aggregate (A) maximum size:	Two levels
NaCl (N), absent or present:	Two levels
Oleic acid (o), absent or present:	Two levels

Each possible combination was replicated, giving a total of 48 experimental units (batches of concrete).

Compressive strength readings were recorded at 2, 4, 26, 52, and 78 weeks (3 cylinders at each period), allowing extrapolations in time to yield asymptotic values of compressive strength.

DATA ANALYSIS

Curves of the following form appeared to fit the data of each of the 48 batches quite well:

$$CS = ACS\left[1 - e^{-k(t - t_0)}\right] \qquad \text{(D-1)}$$

where CS = observed compressive strength

ACS = asymptotic compressive strength, the maximum expected value of compressive strength

k = rate constant which indicates how a small change in a compressive strength is related to a small change in time

t_0 = the time at which the compressive strength measurement is zero

t = curing time in weeks

e = 2.718

Therefore, it was possible to use the value of asymptotic compressive strength as that which would take place after considerable time had elapsed.

Two examples where the compressive strength is subject to the factor combinations of batches SSH-5 and SSL-13 are shown in Table XII with the corresponding values from the fitted least-squares equation. Batch SSH-5 is represented by:

$$CS = 8844\left[1 - e^{-0.028(t + 54.22)}\right]$$

while the corresponding fitted least-squares equation for Batch SSL-13 is:

$$CS = 5107\left[1 - e^{-0.290(t + 2.98)}\right]$$

The asymptotic compressive strengths may be represented by an equation of the form:

$$ACS = e^{b_0 + b_1 S + b_2 A + b_3 N + b_4 o + b_5 SA + b_6 SN + b_7 So + b_8 AN + b_9 Ao + b_{10} No}$$

The parameters, b_i were determined by a least-squares fit on a computer. They were:

b_0 = 8.796 b_6 = -0.089

b_1 = 0.321 b_7 = 0.046

b_2 = 0.014 b_8 = 0.011

b_3 = -0.164 b_9 = -0.004

b_4 = -0.125 b_{10} = 0.110

b_5 = -0.049

Table XII. Examples of Least-Squares Fit to Compressive-Strength Data

Batch No.	Time (Weeks)	Observed Compressive Strengths (psi)			Least-Squares Fitted Compressive Strength (psi)
		Test 1	Test 2	Test 3	
SSH-5	2	6960	6920	6410	7013
	4	7400	7240	7490	7113
	26	7430	8110	8370	7909
	52	7760	8240	8660	8393
	78	8910	8310	8950	8626
					8844[a]
SSL-13	2	4060	3630	4020	3903
	4	4610	4520	4170	4433
	26	5100	5190	5040	5106
	52	5120	5190	5190	5107
	78	5100	5020	5010	5107
					5107[a]

a/ Asymptotic value

Student's t-distribution was used to determine the statistical significance of the parameters. The values of t^2 for the parameters are given in Table XIII.

Table XIII. t-Distribution Test

Parameter	t^2	Remarks
W/C Ratio	246.7	
Aggregate Size	0.2	
NaCl	32.0	
Oleic Acid	18.7	Significance level of t^2 at the 5% level is 4.08, and at the 1% level is 7.29
W/C Ratio - Aggregate Size Interaction	5.7	
W/C Ratio - NaCl Interaction	18.7	
W/C Ratio - Oleic Acid Interaction	5.1	
Aggregate Size - NaCl Interaction	0.1	
Aggregate Size - Oleic Acid Interaction	0.01	
NaCl - Oleic Acid Interaction	10.9	

A least-squares fit on the significant terms (5% level) was performed, giving the equation:

$$ACS = e^{8.803 + 0.321S - 0.158N - 0.127o - 0.049SA - 0.089SN + 0.046So + 0.110No} \qquad (D-2)$$

The correlation coefficient, r, a measure of the goodness of fit of the derived Equation D-2 to the experimental data, was 9.977. This implies a very good fit of the data since 1.0 is perfect correlation.

DISCUSSION

Some question arose when the equation derived did not show aggregate size to be a significant main effect. The data for the factor combinations of medium-strength concrete without NaCl, without oleic acid, and with both small and large aggregate (i.e., S = 0, N = 0, o = 0, A = 0 and 1) showed the large aggregate having higher asymptotic compressive strengths than the small aggregate. However, the compressive-strength variation between the two batches of small aggregate was 600 psi for the fitted curves and 920 psi between the maximum and minimum data points at 78 weeks. The difference between the small-aggregate batch and the two large-aggregate batches at the higher compressive strength was 500 psi at 78 weeks for the fitted curves. The difference for the corresponding data points at 78 weeks ranged from 190 to 660 psi. This would tend to confound the main effect of maximum aggregate size; i.e., it does not appear as a statistically significant factor.

Analyzing the 12 experimental units without NaCl and without oleic acid separately from the remaining 36 experimental units did not produce a statistically significant main effect for aggregate size. An equation of the form:

$$CS = e^{b_0 + b_1 S + b_2 A + b_3 SA}$$

where b_0, b_1, b_2, and b_3 are parameters determined by the least-squares method, showed that b_2 was not a statistically significant parameter. This would eliminate the aggregate size term, and only low- and high-strength concrete would be affected by aggregate size. The latter is attributable to the b_3SA interaction term.

Calculating compressive strengths from Equation D-2 shows that the ranks of the factor combinations from highest to lowest asymptotic compressive strength in terms of the three concrete strengths are:

A. High Strength

1. Small aggregate
2. Large aggregate
3. Small aggregate - oleic acid
4. Large aggregate - oleic acid
5. Small aggregate - NaCl - oleic acid

6. Small aggregate - $NaCl$

7. Large aggregate - $NaCl$ - oleic acid

8. Large aggregate - $NaCl$

B. Medium Strength

1. Small and large aggregate

2. Small and large aggregate - oleic acid

3. Small and large aggregate - $NaCl$

4. Small and large aggregate - $NaCl$ - oleic acid

C. Low Strength

1. Large aggregate

2. Small aggregate

3. Large aggregate - $NaCl$

4. Small aggregate - $NaCl$

5. Large aggregate - $NaCl$ - oleic acid

6. Large aggregate - oleic acid

7. Small aggregate - $NaCl$ - oleic acid

8. Small aggregate - oleic acid

The absence of $NaCl$ and oleic acid consistently gives higher compressive strengths for the three strengths of concrete with both large and small aggregates. The addition of $NaCl$ and/or oleic acid reduces the compressive strength in varying amounts. High- and medium-strength concrete react nearly the same with the addition of these factors, whereas low-strength concrete appears to follow a different pattern. Part of the latter may be due to the small range of compressive-strength values for the low-strength concrete.

Appendix E

ANALYSIS AND CLASSIFICATION — SAN GABRIEL ROCK

A. MEGASCOPIC EXAMINATION OF SG (WVT SPECIMENS)

Group Symbol	Cup No.	Inclination (degrees) of Fabric Plane from Vertical Axis of Cylinder*	Remarks
A	U737	5	Fractured
A	U738	72	Weakly banded
A	U739	65	Weakly banded and fractured
B	U602	40	—
B	U603	40	—
B	U604	87	—
C	U857	—	Fabric not sufficiently
C	U858	—	developed to measure
D	U859	85	Fabric weakly developed
D	U860	85	Healed fracture
E	U861	40	—
E	U862	40	Fractured
F	U863	10	—
F	U864	5	—
G	U865	10	Banded gneiss
G	U866	10	Banded gneiss
G	U867	80	Healed fracture
G	U868	75	Banded gneiss
H	U869	45	Fabric weakly developed
H	U870	45	—

*Fabric is the orientation in space of the crystals of which a rock is composed.

B. PETROGRAPHIC DESCRIPTION AND CLASSIFICATION OF SG (WVT SPECIMENS)

1. Leucocratic Quartzo-Feldspathic Cataclastic Gneiss

Group A shows considerable granulation with abundant large relic grains of feldspar and quartz (up to 1 cm). Cataclastic textures have been partly obliterated by recrystallization of groundmass quartz and alkali feldspar. Feldspars and quartz exhibit pronounced undulatory extinction and sutured grain contacts. Plagioclase is badly saussuritized. Fine-grained quartz and muscovite are oriented along shear planes which give the rock a distinct foliation.

This material is moderately fresh and due to the paucity of mafic minerals it should be relatively resistant to both chemical and mechanical attack.

Mode	Percent
alkali feldspar (including microcline)	40
plagioclase (oligoclase)	15
quartz	30
muscovite	10
garnet	Tr*
clinopyroxene	3
green biotite	2
hematite	Tr

*Trace (less than 1 percent)

2. Hornblende-Clinopyroxene Quartzo-Feldspathic Gneiss

Group B is a coarse-grained (2-4 mm) equigranular rock with granoblastic texture and sutured grain boundaries. Lineation results from preferred orientation of hornblende; weak foliation is due to compositional banding (quartz + feldspar layers alternate with quartz + feldspar + mafic mineral bands). Quartz and feldspars show strain shadows and some myrmekitic intergrowths, but all phases are fresh.

The abundant mafic clots of hornblende + clinopyroxene indicate that, although the rock is as yet unaltered, it is susceptible to chemical attack.

Mode	Percent
alkali feldspar (including microcline)	25
plagioclase (andesine-oligoclase)	30
quartz	25
green-brown hornblende	12
clinopyroxene	4
apatite	Tr
magnetite	2
biotite	2

3. Monzonite Porphyry

Group C is a hiatal porphyry. Large (3 mm) euthedra of strongly zoned (oscillatory) plagioclase are set in a fine-grained, intensely altered mesostasis of alkali feldspar + quartz + mafic minerals. Weak (magmatic) flow banding results from orientation of plagioclase tablets and chlorite + biotite flakes. Primary clinopyroxene has been almost completely eliminated by alteration processes which have sericitized much of the groundmass feldspar. The phenocrysts of intermediate plagioclase are relatively fresh but are susceptible to chemical attack.

Mode	Percent
phenocrysts	
oligoclase-andesine (strongly zoned, fragmented)	25
saussuritized plagioclase (sericite + epidote + calcite)	2
groundmass	
quartz	10
alkali feldspar (including plagioclase)	40
biotite	6
chlorite	14

Mode	Percent
carbonate	2
clinopyroxene	Tr
magnetite	1
hematite	Tr
sphene	Tr

4. Hornblende Quartz Plagioclase Schist

Group D has a medium-grained (2 mm) granular texture with foliation produced by planar orientation of chlorite + biotite and by lineation of hornblende. Long axes of plagioclase + quartz grains are also aligned with this lineation. There are spotty patches of intensely sericitized plagioclase.

Equigranularity of this rock tends to increase its mechanical strength, but chemical weathering of the abundant mafic minerals would decrease its stability.

Mode	Percent
plagioclase (andesine), including saussuritized plagioclase	50
quartz	20
hornblende	13
biotite	4
chlorite	7
clinopyroxene	5
magnetite	1
zoisite	Tr
apatite	Tr
carbonate (calcite)	Tr

5. Coarsely Porphyroblastic Hornblende Quartzo-Feldspathic Gneiss

Group E contains about 20 percent very large (up to 3 x 2 cm) porphyroblasts of microcline set in a medium-grained (2-3 mm) groundmass. Some quartz is slightly strained and shows sutured grain boundaries. The plagioclase, alkali feldspar, and quartz are intergrown in a typical granular (granoblastic) texture; rare quartz-alkali feldspar myrmekite is also evident. The original mafic mineral was probably clinopyroxene but has been largely converted to hornblende, biotite, chlorite, sphene, and magnetite through hydration, oxidation, and recrystallization.

Partial decomposition of mafics and the coarsely porphyroblastic texture probably mean this rock is relatively vulnerable to mechanical and chemical breakdown.

Mode	Percent
alkali feldspar (microcline)	
porphyroblasts	20
groundmass	15
plagioclase (calcic oligoclase)	30
quartz	15
chlorite	3
biotite	7
clinopyroxene	2
magnetite	3
sphene	2
blue-green hornblende	3

6. Fine-Grained Porphyroblastic Biotite Gneiss

Group F is a medium-grained (2-3 mm) granoblastic gneiss with minor porphyroblasts (5-8 mm) of perthitic alkali feldspar and plagioclase. The porphyroblasts have been somewhat milled and give the appearance of small augen in hand specimen. Quartz exhibits strain shadows. Foliation is due to preferred orientation of biotite flakes. Minor myrmekitic intergrowths of quartz and alkali feldspar are present.

This rock in general and the feldspars in particular look very fresh.

Mode	Percent
plagioclase (oligoclase)	20
alakali feldspar (microcline)	30
quartz	35
biotite	13
chlorite	Tr
magnetite	1
hematite	Tr
tourmaline	Tr
apatite	Tr
sphene	1

7. Hornblende-Quartzo-Feldspathic Gneiss

Group G is a foliated granoblastic equigranular gneiss. Quartz shows undulatory extinction and is more or less restricted to specific laminae. Hornblende is sub-oriented in the plane of foliation; mafics in general are "strung out" in this plane. Felsic and mafic minerals are all very fresh.

Abundant hornblende clots probably will cause this rock to alter along shear planes during oxidation.

Mode	Percent
alkali feldspar (microcline)	Tr
quartz	25
plagioclase (calcic oligoclase)	50
blue-green hornblende	20
magnetite	1
sphene	2
clinopyroxene	1
chlorite	1
apatite	Tr

8. Equigranular Biotite Granite Gneiss

Group H is a medium-grained (approximately 3 mm) equigranular gneiss with granoblastic texture. Sutured contacts are common, quartz shows strongly undulatory extinciion, and feldspars exhibit weak twinning. Plagioclase is faintly zoned. Rare wormy intergrowths between quartz and microcline were observed. Feldspars are moderately sericitized and biotite is partly replaced by chlorite.

Mode	Percent
alkali feldspar (microcline)	35
quartz	20
plagioclase (albite-oligoclase)	30
brown biotite	12
muscovite	1
chlorite	1
magnetite	1

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